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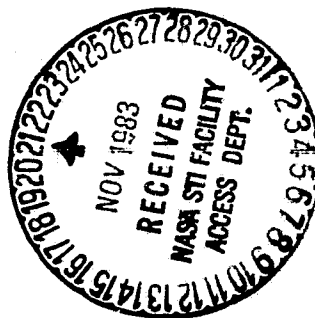
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## SNOWPACK GROUND-TRUTH MANUAL

MAY 1983



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**SNOWPACK  
GROUND-TRUTH MANUAL**

**Prepared for:**

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## PREFACE

As remote sensing increasingly becomes more of an operational tool in the field of snow management and snow hydrology, a need has arisen for some degree of standardization of "snowpack ground truth" techniques. The purpose of this manual is to provide a first step in standardizing these procedures. This report is prepared to meet the needs of remote sensing researchers in planning missions requiring ground truth and also to meet the needs of those who will be providing the ground truth. This manual focuses on ground truth for remote sensors primarily operating in the microwave portion of the electromagnetic spectrum; nevertheless it should be of value to other types of sensor programs. This first edition of ground-truth procedures must be updated as new or modified techniques are developed.

## I. INTRODUCTION

The importance of water resources has been noted throughout history. It is only in the last few decades, however, that researchers have directed attention to the snow portion of these water resources. Snow can be considered in many ways, but from a hydrologic point of view it is "water in storage." The ability to quantify the amount of water in storage and to determine its location is indeed a valuable contribution and step forward in the management of water resources throughout the world. Other major accomplishments include the advent of operational satellites and remote sensing aircraft that can provide qualitative information on the depth of the snowpack, its water content, and areal extent.

The use of remote sensing techniques provides the observer with information in the form of electronic data and signatures. These must be analyzed and correlated with the actual conditions on the surface of the earth at the time the observations were made from the remote sensing platform. Ground truth has been defined as "the realistic presentation of the target for remote sensing experiments or operations" (NASA 1982). Ground-truth data should be collected as a function of a particular mission.

In this manual the primary emphasis will be on ground-truth measurements taken in conjunction with electromagnetic (EM) remote sensing programs. The planning of effective ground truth requires a knowledge of the snowpack as an EM medium and the subsequent interaction of EM waves with the medium. Hence the emphasis is placed on ground-truth information that will aid remote sensing scientists in correlating the perceived electromagnetic signature of the snow with the actual target conditions.

### THE SNOWPACK

When snow exists near its melting point, as it often does, it is one of the most unstable natural substances on earth. This instability is revealed by drastic changes or metamorphism in crystals as soon as they are deposited. The temperature of the layer determines the rate of metamorphism and the temperature gradient across the layer largely determines the type of metamorphism. In a dry seasonal snowpack it is convenient to distinguish the types of metamorphism. If the metamorphism is in response to a strong thermal gradient within the snowpack, the process is called temperature gradient metamorphism. If the process is not driven by the temperature gradient, but develops from the tendency of the snow to minimize its surface free energy, thereby simplifying its structure, the process is called equitemperature metamorphism. A third type of metamorphism occurs when the snowpack temperature reaches 0°C and surface snow layers undergo frequent melt-freeze cycles. Under these conditions the smaller ice grains in the surface layer melt during the day and the melt water refreezes at night. Repeated freeze-thaw cycles produce large rounded clusters of ice grains, commonly known as "corn snow," by a process called melt-freeze metamorphism.

The snowpack as an EM medium is complex and requires rigorous quantitative evaluation. The snow medium is generally nonhomogeneous and stratified.

It can contain snow in several different stages of metamorphism ranging from depth hoar near the ground-snow interface to melt-freeze near the snow-air interface. Snow grain size and shape as well as density varies within the pack usually from one stratigraphic layer to the next and complicates the analysis of the electromagnetic wave-snowpack interaction. Liquid water content in the pack is seldom uniform. Depending on climatic conditions, liquid water content can be greatest at the surface, the middle, or the bottom of the pack.

#### SENSOR RESPONSES TO SNOWPACKS

The planning of effective ground truth requires some knowledge of the response of the detector package. The specific relations reported by NASA (1982) for satellite based sensors are shown in Table 1.

Table 1  
Sensor Response to Snowpack Properties

Property	Sensor	Visible/ near infrared	Thermal infrared	Microwave
Snow-covered area		Yes	Yes	Yes
Depth		If very shallow	Weak	Moderate
Snow water equivalent		If very shallow	Weak	Moderate
Density		<u>1/</u>	<u>1/</u>	<u>1/</u>
Stratigraphy		No	Weak	Strong
Albedo		Strong	No	No
Liquid water content		Weak	Weak	Strong
Temperature		No	Strong	Weak
Snow/soil boundary		No	No	Weak-high frequency to strong-low frequency
-----				
All weather capability		No	No	Yes
Current best spatial resolution from space platform		10's of meters	100's of m	<u>Passive</u> 30 km--high frequency to 150 km low frequency <u>Active</u> 10 meters

1/ Density is determined by depth and water equivalent.  
(NASA, 1980)

The resolution of the sensors shown in Table 1 refer to those located on a satellite. They may however be located on aircraft which fly potentially long flightlines, in which case the resolution is much better. When the sensors are used in a trial or test mode, they can even be truck-mounted on a long boom. This allows the sensors to be located only several meters above a ground target. In this mode the study area may be as small as 10 x 10 meters in which case the sensor resolution is excellent. Experiments involving the interaction of electromagnetic waves with snowpack and using both active radar and passive radiometric systems have shown that depending on the frequency, the interaction is governed by both surface and volumetric effects of the snowpack and may be influenced by the underlying ground surface. The degree to which the snowpack volume plays a role is dependent on snow wetness, stratigraphic layering, ice grain sizes, and observation frequencies. For active radar systems, the characteristics of the interaction are such that snow wetness and snowpack water equivalence exert the greatest influence. Sensitivity to both parameters increases with increasing frequency. Radar backscatter cross sections tend to increase with increasing snowpack water equivalence (SWE) at low frequencies (2 GHz to 15 GHz). SWE is the depth of water which would result if the snowpack were to be melted without loss. However, while the sensitivity increases with increasing frequency, the snow depth at which the snowpack becomes electromagnetically semi-infinite decreases. Above 15 GHz the backscatter is very sensitive to SWE in the range 0 to 20 cm but loses sensitivity at greater SWE (Stiles & Ulaby, 1980). In all cases, the radar backscatter decreases with increasing snow wetness.

For passive radiometric systems the apparent brightness temperature decreases with increasing SWE. A greater range of SWE can be observed at lower frequencies. Small observation angles from nadir (0 to 30 degrees) are also preferred because the emissivity of snowpack is less sensitive to angle in this range. For snowpack wetness or more precise liquid water content, the sensitivity increases with frequency and angle. The brightness temperature generally increases with increasing liquid water content.

ORIGINAL PHOTO  
OF POOR QUALITY



Fig. 1. This scene taken on the flank of Mt. Hood shows typical types of terrain which may be encountered in snowpack ground-truth missions. (Photo courtesy of Soil Conservation Service, USDA)

## II. MEASUREMENT CONCEPTS IN THE FIELD DURING A GROUND-TRUTH MISSION

### INTRODUCTION

Thus far the discussions in this manual have centered upon electromagnetic measurements that are essential to a ground-truth mission in connection with the electromagnetic remote sensing of the snowpack. Before going into the field there needs to be a general plan detailing which measurements are to be taken, how often they are to be taken in terms of time and the spacing of measurements in the study area.

### SNOWPACK GROUND-TRUTH ELEMENTS

The characteristics of the snowpack which must be considered in any ground truth operation that deals with either active or passive microwave systems, and to other systems to some extent, will include snow depth, water equivalence, density, liquid water, snow-grain characterization, and general site conditions. These items are divided into those measurements that are taken on the surface and those that will be taken in a snow pit.

Specific measurements required for each of the above will be discussed in the next section of this Manual.

### OBTAINING ELECTROMAGNETIC DATA

Two methods of obtaining electromagnetic data are commonly used. Active and passive systems mounted on a fixed truck are used to observe specific areas or swaths of snowpack. The snowpack observations for fixed point operations is usually no larger than 10 x 10 meters. Typically an area 10 x 200 meters is used for observing a swath of snowpack.

A second method of obtaining electromagnetic uses systems mounted on aircraft which are flown over the pack or are satellite based. The aerial paths observed are several kilometers long and 400 to 500 meters (1/4 mile) wide. The satellite will "view" a much wider and longer line but accompanying ground-truth observations will normally be treated in much the same manner as aircraft observations.

Different strategies for taking ground truth are employed depending on the type of observation. The ground-truth strategy in each type of experiment is described below.

#### Truck Mounted System

Electromagnetic measurements that use truck-mounted systems usually operate in a continuous mode and can be used to investigate electromagnetic responses as a function of time. For example, changing snowmelt conditions during the day as well as diurnal variations can be investigated. Melting can occur during the day and freezing during the night. Liquid water generated in the surface layer will move in the pack at varying rates which are determined by the stratigraphy and density of each stratigraphic layer. If, however, the air temperature is low enough, significant melting will



not occur, but the surface may be altered by wind packing, newly fallen snow, or blowing snow. Continuous monitoring of the surface condition is therefore important. Liquid water content, temperature, and density can change within the top 20 to 50 cm of the pack. Below this depth, snowpack is generally insulated by the upper layer until sufficient melt water is able to drain through the pack. When melt water is draining through the pack, the condition is known as "ripe snowpack."

When working with a truck-mounted sensor, care must be taken to preserve the target area. Hence, ground-truth measurements must be obtained around the perimeter as established by the mission manager.

### Aircraft Systems

Unlike the truck-mounted systems previously discussed, the aircraft sampling time over a flight line several kilometers long will take place over a relatively short period of time. The passes over the flight line may be repeated at later times.

The overall technical director or manager of the program will normally determine the specific flight lines that are to be flown, the desired number of flights, and the flight schedule. Additionally, specifications may be required on ground-truth measurements and alternative plans if weather problems are encountered. With this information and knowledge of the mission objective, the ground-truth operations manager must then devise an operational plan to obtain the necessary data within the required time frame.

The first task is familiarizing oneself with the specific flight lines to be flown. If the flight lines are new and ground truth has not been performed on them previously, a preflight trip to the site is often essential. The ground-truth operations manager must be able not only to organize the collection of ground-truth data but must attend to those factors which involve the safety and welfare of the personnel. Should serious problems arise on this preflight trip over the flight lines (such as insufficient snowpack or partial snowpack conditions), arrangements must be made with the overall technical director or project monitor to either modify ground truth requirements and/or the flight lines so that problems can be minimized.

### SATELLITE SYSTEMS

Ground truth in connection with a satellite system can be approached in much the same manner as that outlined for aircraft systems. The exception might be that several sites might be simultaneously involved.

### SURFACE MEASUREMENTS AND OBSERVATIONS

The parameters normally measured on a ground-truth mission include characteristics of the snow surface, near-surface liquid water, snow depth, snow-water equivalent, and snowpack density.

One important item to include is an overall discussion or series of photographs describing the site. This would include such items as snowdrifts, indications of blowing snow, undulating terrain, general surface roughness, etc.

Surface measurements also normally include some determination of near-surface liquid water. When working with microwave remote sensing devices, this is a very important parameter.

Several teams consisting of two people are usually used during a flightline mission to take measurements of snow depth, snow-water equivalent and snowpack density. On truck-mounted missions, these same measurements would be taken but only at selected sites. Snow-depth measurements are normally taken at 30-meter or 100-foot intervals. The spacing of the intervals is easily determined by using a light cord or rope. The lead person carries the rope to the next location and the second person standing at the first location calls out when the 30-meter or 100-foot mark is reached. The second person then joins the first person, and so on. An example of this procedure is shown in Fig. 2.

Snow-water equivalent and snowpack density are normally taken every 150 meters or 500 feet. Since the snow-density and water-equivalent measurements will be taken by the same crew involved in measuring snow depths, every fifth snow-depth measurement will be accompanied by water equivalence and density measurement computations. The writer recommends that at each point where snow density and water equivalence is measured and computed, the ground-truth team note carefully, in methodical form, the surface characteristics of the snowpack. This would include estimates of ski or snowshoe penetration into the snowpack, crystal size, and a brief snowball test to estimate the liquid water content of the snowpack. The categories for estimating liquid water content are quite simple. If no snowball can be made, record the snow as dry. If a snowball can barely be made, note it as slightly moist. If a good solid snowball can be obtained without any water appearing on its surface, it should be recorded as moist. Finally, if water should appear on the snowball while compacting it, it should be recorded as either very moist or in extreme cases as slushy. Such notations obviously rely upon the judgment of the observer. They may, however, be of some value to personnel analyzing ground-truth data in connection with interpreting the remotely sensed data obtained during the experiment.

#### Snowpit Measurements and Observations

Snowpit measurements will provide profiles of snow density, snow temperature stratification, snow crystal size and shape by strata, and snowpack profile of liquid water content. If the snowpit is dug down to ground level, a series of soil samples are normally taken along with indications of underlying vegetation.

Normally at least one snowpit per flight line should be dug and analyzed. The number of snowpits dug would depend upon the variations observed in the field. Except when working in areas where considerable drifting is taking place, a single snowpit can be representative of several kilometers of a flight line or a small test area. Although minor differences will occur along this line, one pit can normally provide fairly realistic results. If



Fig. 2. Snow surveyors using a cord to measure distances between snow sampling points. (Photo courtesy of Soil Conservation Service)

time allows, a second pit should be dug for confirmation. If multiple pits are used, it is recommended that they represent differing snowpack conditions. Once the snowpit has been dug, profiles of density, temperature, and crystal size and shape should be made. If the mission requires it, profiles of liquid-water content could also be done. Since this is very time consuming and requires using a cold calorimeter, these liquid-water content measurements are usually taken only from the top 2 or 3 inches.

If the snowpit is dug to the soil beneath the snow, soil-moisture samples should be taken. It is also important to note conditions that exist on the ground and in the top few centimeters of the soil. It is important that any data taken from a snowpit be carefully documented and recorded in such a way that those responsible for reducing the notes will know whether the observer is making notations from the top of the pit down or from the bottom of the pit up. This very simple procedure is often forgotten and causes a great deal of confusion. In some snowpacks the bottom is easy to determine since the depth hoar occurs normally on the bottom of the snowpack and not on the top. If the snowpit is to be occupied for any length of time, the only repeatable datum will be that of the soil surface.

When liquid-water content measurements are taken by a cold calorimetric method, a series of thermocouple probes or thermister probes are taken into the field. These probes are also normally used in connection with taking the temperature profile of the snowpack. Since the probes are available, various measurements of air temperature should also be taken periodically. When taking these measurements it must be remembered that in order to get a reasonably accurate air temperature, the probe needs to be in the shade a meter or two above the ground and needs to be well ventilated. The probe must remain in this sheltered and ventilated condition until the indicated temperature stabilizes.

A final word on snowpits in the field must include the admonition that these pits can be hazardous to snowmobilers. When left open for extended unattended times they should be flagged. Upon completion of the ground-truth mission all snowpits must be filled. Garbage and other material should not be buried in such pits.

#### General Comments

THE GROUND-TRUTH TEAM IN THE FIELD MUST REMEMBER AT ALL TIMES THAT THEY ARE THE EYES AND EARS OF THE PEOPLE WHO WILL USE THE GROUND-TRUTH DATA AT A LATER TIME. Therefore, even seemingly trivial information may be of help if properly noted and duly recorded. All measurements, at discreet intervals, should be noted with respect to time whenever possible. This is very important because snowpack characteristics change with time. Also the sensor platform is recording time as the remotely sensed data are acquired. Small procedures, such as noting the first, second, third pass, etc., of the aircraft over the area, can often be quite helpful. Similarly, meteorological conditions can also play an important role in changing the signature over very short periods of time. Other than precipitation events, which will be discussed later, these would include occasions when the sun shines brightly after a cloudy morning, time of first sunlight on the site, or a change in wind velocity or direction, start of blowing snow, etc. The best rule to remember for everyone involved in ground truth is that SOMEONE

ELSE WILL BE REDUCING THE DATA OR USING IT TO ANALYZE REMOTELY SENSED SIGNATURES--WILL THEY HAVE ENOUGH DATA AND IS IT CLEARLY PRESENTED? DETAIL IS IMPORTANT.

#### DATA REVIEW

Experience over the years in taking ground-truth data indicates the importance of reducing or at least reviewing the notes of the various field teams at night while still in the field. This review includes such items as completeness, attention to detail, and a statistical analysis of the data collected. This statistical analysis is primarily applied to snow depths, snow densities, and water equivalents. Most users of ground-truth data normally prefer to have the data divided into segments that are easily defined on the ground as well as on maps (i.e., section lines, roads, etc.). Depending upon readily observable features from both ground and air, these distances may vary along the same line from segment to segment. Snow depths are normally tabulated to obtain the mean as well as the maximum and minimum values, the standard deviation and the coefficient of variation (coefficient of variation is the standard deviation divided by the mean). One can then compare these statistics on snow depth by each segment. Similarly the same statistics can be computed for water equivalence and snow density. In this case there should be about 10 or 11 points per segment to provide an adequate statistical sample.

If highly variable conditions are encountered in the field and the mission is still not completed, these conditions should be reported immediately to the overall mission technical monitor. At that point the pattern for taking ground truth may be changed. Should the field statistics be highly variable, a decision must be made as to whether this variation is reasonable. If not, detailed discussions with the field crews need to be held before further sampling is undertaken. Even the best and most experienced ground-truth crew member may occasionally become tired or cold and therefore not as attentive in taking the data. The quality of the field data must be monitored before the mission is completed. Onsite statistical analyses should aid the team leader to get a first cut at the overall quality of the data as well as the natural variations that are occurring.

If a line or area is sampled over more than one day and the snow is believed to be uniform over the entire line and no changes are expected (additional precipitation, blowing wind, rapid changes in temperature, etc.), statistics from the first day's data may provide a guide to the sampling pattern for the second day's data. Likewise, ambiguities in the data may dictate a resampling program requiring more detailed data. Should the data appear uniform, then perhaps the snow-depth measurements can be stretched to 60 meters (200 feet) and snow density and water equivalent measurements at 300 meters (1,000 feet). This stretching of data points will allow either less field time or an opportunity to cover more area.

#### PRIORITIZATION

It is often necessary on a snow mission to prioritize the data. Decisions as to which data should be collected first, second, etc., must be made. If one must make a choice between two items of data, the item most important to the mission should take precedence. Normally such discussions are

theoretical and are held with the overall project technical monitor prior to going into the field. However, in some cases it may be up to the ground-truth manager to make such decisions. These decisions should normally be made on the basis of the measurements which will be constant over a period of time. For example, if an aircraft flight collects data at a time when snowpack conditions are changing rapidly, it is essential to have snowpit data and liquid-water content also collected at the time of the overflight. Thus, some personnel on the ground-truth team should be taking snow depth and density, while others are conducting liquid water and snow pit measurements. Since there may not be enough time to take depth and density data over the entire line, the line should be sampled at selected intervals and the line measurements completed at a time after the overflight.

Another time when data prioritization becomes important is when the ground-truth team is in the field one day prior to the airborne flight and has collected depth and density data during the first day. If it then snows that night, in order to account for the new snow, techniques to correct the data already taken can be utilized when new snows are very light and when the snowpack is at least 20 to 25 times the depth of the new snow layer. If significant snowfall occurs overnight between the time data concerning depth and density is collected and the time the flight should begin the next day, then it is normally necessary to repeat the ground truth in terms of depth and density along the flight lines.

When dealing with truck-mounted sensors, prioritization can be discussed with the personnel actually taking the remotely sensed measurements. This prioritization procedure is much simpler than in the case of the aircraft mission.

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Fig. 3. Tracked over-the-snow vehicles or snowmobiles can be quite useful in reaching remote sites. (Photo courtesy of Soil Conservation Service)

### III. TECHNIQUES FOR PERFORMING SNOWPACK MEASUREMENTS

#### INTRODUCTION

The concepts of a basic set of snowpack parameters to be measured when obtaining ground-truth data in connection with electromagnetic remote sensing systems was developed in the previous section. This section details the methods of obtaining the measurements.

#### SNOW DEPTH

Snow depth is normally measured with a snow probe graduated in either English or metric units. In some cases a specially designed steel or aluminum probe is used. Such a probe is normally made of solid metal that is slightly sharpened at one end to penetrate ice layers as necessary. The probe should be etched with either metric or English depth markings, whichever is preferred. Regardless of the device chosen, length will be governed by the depth of the snowpack which one intends to measure. When taking snow-depth measurements, one must be careful that the snow tube or probe truly reaches ground level. In some cases it is quite easy to construe an ice layer as being the bottom of the snowpack. The best way to verify that the snow tube reaches ground level is to look for soil or litter on the tip of the tube.

Snow is often redeposited by wind. Thus, when planning to make snow-depth measurements, ground-truth personnel must take into account increased depths that may be caused by drifting conditions. Proper site selection can minimize drifting effects so that a site with uniform snow depth is obtained.

Observations are also important in conveying information about the shape of the snowpack surface. If one is working over undulating terrain, it is important to note whether the sample is being taken at a low point, on a slope, or at a high point. Similarly, if sampling is being conducted on a gentle slope, one should attempt to make an estimate of the slope.

#### SNOW-WATER EQUIVALENT

The snow water equivalent of a snowpack is the depth of water which would result if the snowpack were to be melted without any loss. Snowpack water equivalence is defined as an equivalent mass of water as would exist if the same mass of snow were melted. That is,

$$M_w = M_s$$

therefore  $\rho_w V_w = \rho_s V_s$

V = Volume  
M = Mass  
 $\rho$  = Density  
d = Depth  
w = Water  
s = Snow





Fig. 4. Soil Conservation Service snow surveyors taking depth, density, and snow-cover equivalent measurements. (Photo courtesy of Soil Conservation Service)

Snow samples are usually taken with a sampling tube so that the volume can be expressed as Area x Depth. Since the same area is used for the measurement,

$$\rho_w d_w = \rho_s d_s$$

$$\text{and} \quad d_w = \rho_s / \rho_w d_s$$

$d_w$  is the water equivalent depth

To obtain this measurement some form of a "snow tube" is used. The snow tube is normally a lightweight hollow tube with depth markings on the side. The tube is inserted into the snowpack and a snow core is obtained. The weight of this snow core is then converted to the equivalent amount of water held in the snowpack. For example, in the "Federal Sampler" the inside diameter of the cutter bit 1.485 inches (37.7 mm) is such that each inch of water equivalence in the snow tube weighs 1 ounce (28.35 grams). The weight of snow in the snow tube is ascertained by first weighing the snow tube, including the snow core, and then subtracting the weight of the empty snow tube. Fig. 4 shows the snow sample being taken.

Snow tubes normally come in sections about 2½ feet (0.76 m) long. The lower section contains a cutter bit at the bottom. It is important that the cutter bit be kept clean and sharp. The snow tubes can be assembled into an appropriate length so that they will penetrate through the deepest portions of the snowpack. The typical components of the snow sampling kit used by the Soil Conservation Service (USDA) are:

- \* Sections of snow tubes (Federal Sampler)
- \* Spanner wrenches for unscrewing sections that have become stuck
- \* Thread protectors to be used on the last section of the assembled sampler
- \* A driving wrench for pushing the tube down through deep snow with numerous ice layers
- \* A weighing scale and cradle
- \* Field notebook data sheets
- \* Measuring tape

In addition to the above items, which are shown in Fig. 5, the kits normally include a first aid packet, cleaning tools, waxing kit, pencils, and whatever items may be necessary for efficient field operations.

When driving the tube into the snowpack, one should avoid plunging the tube. Instead, a steady downward thrust is preferable. However, some amount of twisting may be necessary to facilitate the quick cutting of thinner ice layers. The snow tube, once driven through the full depth of the snowpack, should be removed quickly after the depth of penetration has been noted. Along the sides of most snow tubes used today there are a series of slots which allow the observer to read the depth of the core.

For reliable measurements the depth of the core should be at least 90 percent of the snow depth. This, however, is sometimes difficult to achieve in very low density snow (powder snow) or in very mushy snow. The reason for checking core length is to insure that no portion of the core is lost in the hole or that the cutter pushed snow to the sides away from the cutting edge.

A snow tube is simple to operate, but in certain types of snow it is sometimes difficult to retain the full core. In such cases it may be necessary to firmly push the snow tube into the soil below the snowpack and take a small soil plug in order to retain the entire core. It should be noted that before weighing the snow tube with the snow core, all of the soil plug, as well as any ground debris must be removed. In many cases this will be a standard operating procedure. The depth of the soil plug must also be subtracted from both snow depth and core length readings.

Once the snow tube has been retrieved and the core length checked, the snow tube is placed on the cradle of the scales. The combined weight of the snow tube and snow are read on the specially calibrated scales which read directly in inches of water equivalent. The tube is then emptied of snow and re-weighed to determine its empty or tare weight. The difference between the combined weight of tube plus cores and the tare weight is the snowpack water equivalent. Once this water equivalent of the snowpack has been determined, the tube should be cleaned and tare weight measured before going to the next point. Under some spring conditions, snow may freeze inside the tube and be relatively difficult to remove. This problem can be



Fig. 5. Components of Federal Type snow tube kit.  
(Resource Consultants, Inc., photo)

alleviated to a great extent by coating the inside of the tube with a film of silicone oil. This is usually accomplished by spraying the inside of the tube with the oil and then drawing a cloth through the tube to remove the excess. If these conditions persist, the tare weight of the tube must be determined each time a sample is taken. Care must be taken to assure that the snow tube is driven to the desired depth--normally the soil surface. To insure this, the cutting tip should be examined for evidence of soil material. A minimum of five separate samples is recommended per measurement. The spread in the individual sample densities on a uniform snowcourse should be within 5 percent of one another. When using a Federal Sampler in snowpack less than 1 meter in depth, it may be necessary to take several cores, each to be deposited in a suitable container (plastic bag, bucket, etc.) in order to obtain a sufficient weight of snow for accurate measurement. Snow water equivalence is determined by dividing the total snow-water equivalence of the aggregate by the number of samples taken.

As discussed above, various types of snow tubes have been developed for various types of snow. The Mount Rose or Federal Sampler has long been a standard for use in the deeper snowpacks of the Rocky Mountain region. The Adirondack snow tube, which is a 1.524 meter (5-foot) long 1-piece fiberglass unit of 67.437 mm (2.655 inches) internal diameter with a metal cutter has been used in the shallow snowpacks of New England with reasonable success. The relative accuracy of these snow tubes has also been studied. In a publication by Work et al. (1965), an accuracy study showed that the Adirondack Sampler oversampled by about 2 to 3 percent resulting in an overweight of the same amount. The slotted Federal Sampler oversampled by nearly 11 percent. A glacial sampler has been used in experiments in determining accuracy of snow pillows near Rabbit Ears Pass (Smith & Boyne, 1982). The glacial sampler produced results within about 2 percent of density profile measurements, whereas the Federal Sampler results were in error by 8 percent. The glacial sampler takes a core with a cross-sectional area of 81.9 cm<sup>2</sup> and is suited to fixed-point measurements of snowpacks. The Federal Sampler, on the other hand, is light, portable, and well suited to long line sampling. A comparison of different snow tubes and the appropriate correction factors is shown in Table 2.

The Western Snow Conference Metrication Committee has been studying the problems of overmeasurements in the Federal type of samplers. They have concluded that a small diameter metric sampler can be designed with a cutter diameter that does not overmeasure. The diameter would be such that 1 gram of weight would equal a decimeter of water equivalent. This sampler would be suited to deep snow as is the current Federal Sampler. They also propose a second metric sampler which would have a sampling area of 30 square centimeters and would be used in snow depths of less than 1 meter. (Farnes et al., 1982).

Regardless of the particular snow tube utilized, the accuracy and ability of the observers should be tested periodically. To accomplish this, it is recommended that a uniform snowpack be sampled numerous times by the same observer and the results carefully compared. This procedure will also aid in training new personnel who are not familiar with the operation of the snow tube.

Table 2  
Overmeasurement of Snow-Water Equivalent  
and Correction Factor for Various Snow Samples<sup>1/</sup>

Type	Cutter area (cm <sup>2</sup> )	Overmeasurement (%)	Correction factor <sup>1/</sup>
Glacier (used as ground truth)	81.9	0	1.00
Standard Federal	11.2	10.0	.91
Sharpened Federal	11.2	6.2	.94
1978 Metric (short)	10.0	7.6	.93
1978 Metric (long)	10.0	4.0	.96
1979 Metric	10.0	7.6	.93
1980 Metric	10.0	4.5	.96
1981 Metric	10.4	3.8	.96
ESC 30	30.0	-0.3	1.00
Aluminum tubing	77.1	0.6	.99
ESC 50	50.0	-0.1	1.00
PVC Tubing	20.9	0.0	1.00
ESC 40	40.0	0.2	1.00
Broken-tooth Federal	11.2	12.1	.89
BUNG	11.2	4.7	.96
McCall	11.2	4.5	.96
Adirondack	35.7	-0.2 <sup>2/</sup>	1.00
CRREL Tubes (Volume = 500 cm <sup>3</sup> )		7.1 <sup>2/</sup>	.93
Rosen	11.2	4.1	.96
Bowman	11.2	4.6	.96
Leopold and Stevens	11.2	8.2	.92
MSC	39.1	7.0	.93
Utah	11.2	5.6	.95

<sup>1/</sup> To obtain true SWE with various samplers, multiply measured SWE by the correction factor.

<sup>2/</sup> All tests in shallow snow in Alaska.

BASED ON DATA OBTAINED BY METRICATION COMMITTEE AND OTHER STUDIES OF SNOW SAMPLER ACCURACY. COMPARISONS MADE WITH GLACIER SAMPLER WHEN DATA AVAILABLE; OTHERWISE, COMPARISON MADE WITH STANDARD FEDERAL OR COMBINATION OF GLACIER AND STANDARD FEDERAL.

(From: Farnes et al., 1982)

#### SNOWPACK DENSITY

The specific gravity of a snowpack by definition is the water equivalence divided by the depth. Since both snow depth and the water equivalent are expressed in units of length, the resulting quotient indicates the specific gravity.

$$\text{Specific gravity} = \frac{\text{snow-water equivalent}}{\text{snow depth}}$$

## LIQUID WATER

The liquid water content of a snowpack, sometimes called free water, snow water content, or liquid phase water, includes two categories of water: gravitational water moving downward through the snowpack and capillary water held by surface tension in the snow matrix. The amount of liquid water is a parameter that is important in predicting the timing of wet avalanche release and in the interpretation of snowpack remote sensing data using microwave techniques. However, this is not a regularly reported snowpack characteristic due to the difficulties of measuring liquid water in the field. Liquid water in a snowpack, not to be confused with water equivalence, has been recognized for some time as a quantifiable parameter of hydrological significance.

Various techniques have been used or proposed to measure the liquid water content of a snowpack. Most of these techniques can be broadly categorized as centrifugal, dielectric, and calorimetric and range from laboratory techniques to remote sensing concepts. Some investigators have tested additional methods. Shoda (1952) used a measurement of volume expansion upon freezing, and Bader (1948) used the concept of dilution of a solution by the liquid water in the snowpack.

Centrifugal separation of the liquid water from a snow sample was described by Kuroda and Furukawa (1954), Carroll (1976), and Langham (1978). This method should not be used to determine liquid water. The centrifuge technique has been compared with the calorimetric technique by the National Bureau of Standards (Jones 1979). The Bureau concluded that the centrifuge and freezing calorimeter method results do not measure the same phenomena. Water may be present in the snowpack in a form which is detectable by the freezing calorimeter method but not by the centrifuge method. (Colbeck 1978)

The measurement and comparison of the dielectric constant of wet and dry snow has provided a method of determining the liquid water content of the snowpack (Ambach & Denoth, 1974). Linlor et al. (1975), Linlor & Smith (1974), and Linlor et al. (1974) have used several methods for measuring the liquid water based on the dielectric constant, as well as experimenting with the attenuation of microwave beam transmission through a snowpack. These methods, however, require calibration.

Several calorimetric methods have been proposed. The melting of a given quantity of snow with a measured amount of hot water and the recording of resulting temperatures has been used (Yoshida, 1940; 1960; 1967). However, this method is difficult to use in the field. A related procedure that employs the melting of a snow sample by a measured amount of electrical energy was described by de Quervain (1946) and Hansen & Jellinek (1957). Another class of calorimetric techniques in which a measurement is taken of the "negative heat" required to freeze a snow sample was described by Radok et al. (1960) and has been effectively used in the field by Leaf (1966). Howell et al. (1976) and Bergman (1978) have utilized the freezing calorimetric technique with toluene as the freezing agent. Although toluene is a very satisfactory freezing agent, its toxic properties and relatively low flash point make its use undesirable. A light silicon oil is an excellent substitute for the toluene, thus avoiding toxicity and flash point problems.

Nonetheless the freezing calorimetric approach appears suitable for liquid water determinations. This method was selected for detailed discussion primarily because it is relatively inexpensive, is based on known and documented physical phenomena, and has been used as a method for calibrating other techniques. In addition, it appears that because a small amount of liquid water is frozen in the cold calorimetric approach as opposed to a large amount of snow melted in the hot water calorimetric method, the freezing calorimetric method is more sensitive to variations in liquid water content. Leaf (1966) and Langham (1974) estimated that the freezing calorimetric method has errors of about  $\pm 1$  percent of the liquid water content by weight.

A detailed discussion of specific procedures for utilizing this technique is presented in Appendix A.

The freezing calorimeter technique is time consuming and does require equipment as set forth in Appendix A. It is not viewed as the ultimate answer in field measurements of liquid water, but is used as a method which serves as a baseline for other techniques. It becomes a check by virtue of the fact that it is readily explainable through calorimetry theory and has a sound physical basis. However, field conditions are not the best place to operate this technique at maximum efficiency or accuracy.

The cold calorimeter technique should definitely be practiced in a laboratory by personnel-in-training before they use it in the field. After personnel are familiar with the technique they can teach others how to use it.

#### SNOW GRAIN (CRYSTAL) CHARACTERIZATIONS

Snow crystals are constantly undergoing a metamorphism or change due to freeze-thaw cycles, temperature and vapor gradients. Redeposited or drifted snow will exhibit different characteristics than those of freshly fallen snow in that the crystals tend to be shattered and then closely compacted. These factors must be considered when one is attempting to characterize the snow crystals in a snowpack.

The size and characteristics of snow crystals or grains can have a profound influence on microwave radiation. They can also influence visible and near IR surface measurements. Over the years various snow-crystal classification schemes have been presented. An example of the classification of airborne snow flakes is the one presented by Magono & Lee (1966, 1968) in Fig. 6.

However when taking ground-truth data, one is primarily interested in characterizing the grain types in the snowpack. The classification scheme described in the following sections is based on the technique described by Sommerfeld and LaChapelle (1970). Symbols describing the snow-grain characterization are those described by UNESCO/IASH/WMO (1970). This

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






























	N1a Elementary needle		C1f Hollow column		F2b Stellar crystal with sectorlike ends
	N1b Bundle of elementary needles		C2g Solid thick plate		F2c Dendritic crystal with plates at ends
	N1c Elementary sheath		C1h Thick plate of skeleton form		F2d Dendritic crystal with sectorlike ends
	N1d Bundle of elementary sheaths		C1i Scroll		F2e Plate with simple extensions
	N1e Long solid column		C2a Combination of bullets		F2f Plate with sectorlike extensions
	N2a Combination of needles		C2b Combination of columns		F2g Plate with dendritic extensions
	N2b Combination of sheaths		F1a Hexagonal plate		F3a Two-branched crystal
	N2c Combination of long solid columns		F1b Crystal with sectorlike branches		F3b Three-branched crystal
	C1a Pyramid		F1c Crystal with broad branches		F3c Four-branched crystal
	C1b Cup		F1d Stellar crystal		F3d Broad branch crystal with 12 branches
	C1c Solid bullet		F1e Ordinary dendritic crystal		F3e Dendritic crystal with 12 branches
	C1d Hollow bullet		F1f Fernlike crystal		F3f Palmformed crystal
	C1e Solid column		F2e Stellar crystal with plates at ends		F3g Plate with central plates

Fig. 6. Meteorological classification of snow crystals, sketches. (Magono & Lee, 1968)



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	P6b Plate with spatial dendrites		CP5d Plate with serrails at ends		R5c Graupellike snow with nonrimed extensions
	P6c Stellar crystal with spatial plates		S1 Side planes		R6a Hexagonal graupel
	P6d Stellar crystal with spatial dendrites		S2 Scalloped side planes		R6b Lump graupel
	P7a Radiating assemblage of plates		S3 Combination of side planes, bullets and columns		R6c Conelike graupel
	P7b Radiating assemblage of dendrites		R1a Rimed needle crystal		I1 Ice particle
	CP1a Column with plates		R1b Rimed columnar crystal		I2 Rimed particle
	CP1b Column with dendrites		R1c Rimed plate or sector		I3a Broken branch
	CP1c Multiple capped column		R1d Rimed stellar crystal		I3b Rimed broken branch
	CP2a Bullet with plates		R2a Densely rimed plate or sector		I4 Miscellaneous
	CP2b Bullet with dendrites		R2b Densely rimed stellar crystal		G1 Minute column
	CP3a Stellar crystal with needles		R2c Stellar crystal with rimed spatial branches		G2 Germ of skeleton form
	CP3b Stellar crystal with columns		R3a Graupellike snow of hexagonal type		G3 Minute hexagonal plate
	CP3c Stellar crystal with serrails at ends		R3b Graupellike snow of lump type		G4 Minute stellar crystal
					G5 Minute assemblage of plates
					G6 Irregular form

Fig. 6 (continued)

description of snowpack metamorphism may be revised as continuing research leads to a more complete understanding of metamorphic processes (Colbeck, 1982; Sommerfeld, 1983).

After the snow reaches the surface, metamorphism will soon begin. The metamorphism may be equitemperature metamorphism (ET), temperature gradient metamorphism (TG), or melt-freeze metamorphism (MF).

#### ET Metamorphism

Equitemperature metamorphism is caused by a variation in the saturated vapor pressure at the surface of the snow grain. Generally for snow grains at constant temperature, higher vapor pressure can be supported over a convex surface than over a flat surface and higher vapor pressure can be supported over a flat surface than a concave one. Therefore, a vapor pressure difference is evident between the convex and concave surface and consequently there is a net transfer of water vapor from convexities and crystal corners and dendritic branches to concavities. The result of this preferential transfer of vapor causes three important changes in snow texture: (Perla & Martinelli, 1976)

- (1) General rounding of the grains.
- (2) Strengthening of the snow matrix by formation of necks between the grains.
- (3) Change in grain size.

The rate of change increases with increasing temperature, becoming very rapid near the melting point and almost nonexistent at  $-40^{\circ}\text{C}$ . As a result of ET metamorphism, sharp corners and fine branches associated with newly fallen snow disappear and the apparent size of the snow grain begins to decrease. At warm temperatures, these changes require a few hours, in cold temperatures, a few days. The ET metamorphism proceeds until the original shape can no longer be identified. Grains become more rounded and large grains tend to grow at the expense of smaller grains. In the final stages of ET metamorphism, there is a strong tendency toward uniform, well rounded, bonded grains. (See Appendix B)

#### TG Metamorphism

Vapor pressure over an ice surface is temperature dependent. The higher the temperature, the higher the vapor pressure. The fact that vapor pressure depends on temperature means that more vapor can be supported in a warm pore space between the ice grains than in a cold pore space. This implies that if a temperature gradient exists within the snowpack, vapor will flow from high to low temperature regions of the snowpack. The vapor flow is thought to diffuse from the warmer grains across the pore space to neighboring colder grains. The resulting change in the ice skeleton is called temperature gradient metamorphism. For heat energy to be transferred efficiently, vapor is deposited on the grains instead of on the necks between the grains. Thus, during TG metamorphism individual grains enlarge while the neck thickness remains essentially constant. This is in direct contrast to ET metamorphism in which the neck regions grow at the

expense of grain convexity. TG grains are characterized by flat, sometimes step-like, striated faces. The faces intersect forming sharp angular corners that give the grains a coarse texture as compared with the rounded small grains of ET metamorphism. In the advanced stages of TG metamorphism, TG grains enlarge to several mm in diameter and have very distinct faces and corners. These large TG grains are called depth hoar.

Because grains of newly fallen snow contain sharply curved concave and convex regions, there is an initial tendency to simplify the shape of the newly fallen snow by mass transfer from convexity to concavity. Therefore, metamorphism of a newly fallen snow layer is ET controlled. After the crystal becomes a small and well rounded grain, ET and TG processes compete for control. Generally, ET processes are dominant if the temperature gradient is less than  $1^{\circ}\text{C}$  per 10 cm of snow and TG processes are dominant if the temperature gradient is greater than  $1^{\circ}\text{C}$  per 10 cm of snow. (Boyne, 1982)

### MF Metamorphism

The development of coarse, rounded grains within a warm or wet snow layer or snowpack is the result of melt-freeze (MF) metamorphism. At or near the snow surface, the process is due to melting and refreezing. Deep in a warm snowpack, the process is related to the slight difference in melting temperature between small and large snow grains, leading to the disappearance of small grains and the enlargement of larger ones. (U.S. Geological Survey, 1977)

A more complete description of the various stages of of snow metamorphism can be found in Appendix B.

### Characterization Techniques

Two approaches are used to characterize snow crystals in a snowpack. The first is by the use of a hand lens with a calibrated reticle for accurately characterizing sizes of the individual snow crystals or aggregated groups of crystals. The hand lenses with the reticles are available from various scientific supply houses. The reticles which are most popular are those which are calibrated in millimeters on a square grid. Normally these are laid out in rectangular form with 10 divisions of one millimeter on each side. Experience with this type of reticle has been quite good. The magnification required is not normally more than that obtained with a common hand lens. The second approach is similar except that observations are recorded on film. This is done by using a photographic arrangement in connection with a very low powered microscope. Gridded reticles are also used in this arrangement. Examples of such photos are shown in Appendix B.

When viewing, one must also be able to describe intelligently what is being observed. The best way to train people to understand what they are seeing is to have them review a crystal classification system complete with photographs so that comparisons can be made with a known classification. An example of such material and classification system is presented by R. A. Sommerfeld (1969). His paper "Classification Outline for Snow on the Ground" is included in its entirety in Appendix B. Another valuable handbook is the Field Guide to Snow Crystals by LaChapelle (1969). Care

should be exercised in training observers to determine snow-crystal types and characteristics quickly and adequately. A suggested manner for accomplishing this training is to work with groups of two or three with observer trainees in sampling snow from the surface in a very limited area. In this way they should all be looking at similar samples of snow. In order to analyze snow adequately, one must spread the snow crystals out thinly over a dark background such as the palm of a dark glove. This training exercise should be conducted using various types of snow. It may take a few sessions to train the observers so that they make consistently good observations. With new observers it is desirable to have them practice in teams of two for discussion on types of classification.

#### SURFACE ROUGHNESS CHARACTERISTICS

Surface roughness characteristics and slopes also tend to have an impact on microwave signatures. Various methods have been tried over the years to adequately characterize surface roughness. Most of these tend to be photographic by nature since it is easier to obtain the documentation this way than in other manners. Normally a dark plate (marked with lightly colored etched lines on a grid of roughly 1 centimeter) is inserted vertically into the snow and leveled so that the lines are horizontal and vertical. One can then step back and take pictures at various angles against this dark background. It is also important to note the surrounding large-scale roughness. This can normally be documented by photographs. However, in those cases where the mission requires large-scale roughness detail, a mapping procedure may be needed.

#### SNOWPIT PROFILES

Snow pits are dug in order to determine the vertical distribution of density, temperature, grain type, and liquid water. Snow pits are relatively easy to dig and are useful for interpreting electromagnetic responses. It is common practice to measure the amount of snow on the ground by probing and to refer to it as snow depth. However, snow profiles are plotted in terms of the height above the ground due to the constantly changing snow surface, which provides a poor reference plane. Snow pit data should generally be taken from the north facing wall (northern hemisphere) as soon as the pit is excavated. This is especially critical in spring when pit walls are likely to heat up rapidly. The snow pit has to be large enough in cross-sectional area (usually 3 x 4 feet) to make observations without continuously disturbing the pit wall and altering snow characteristics on the wall by body heat transfer. Gloves should also be worn to reduce heat transfer when making measurements on the pit wall. The pit wall should be smoothed with the tip of a shovel and then gently brushed with the horizontal strokes of a soft brush to bring out stratigraphic variations. The first thing to look for is the stratigraphic layers in the snowpack. In the deep snowpack of maritime climates these may be layers of cold dry snow or thick layers of hard ice, developed from earlier melt-freeze metamorphism of old surface layers. These layers can become impermeable layers and cause melt water ponding in the pack during the melting season.

## Density

The density of layers in a snowpack can be measured using a small sampler pressed horizontally into the snowpit wall. This sampler measures like a snow tube, but is only a few inches long. Various configurations of these types of samplers are available commercially, as well as from machine shops. If one is to make a sampler, the inside volume of the tube must be determined so that when the snow content is weighed (total weight minus tare weight), the density can be determined. A water equivalence can then be computed if the density and the length of the snow tube are known. Commercial kits of this nature are available. One such kit which uses a rectangular cutter for obtaining snow samples is shown in Fig. 7.

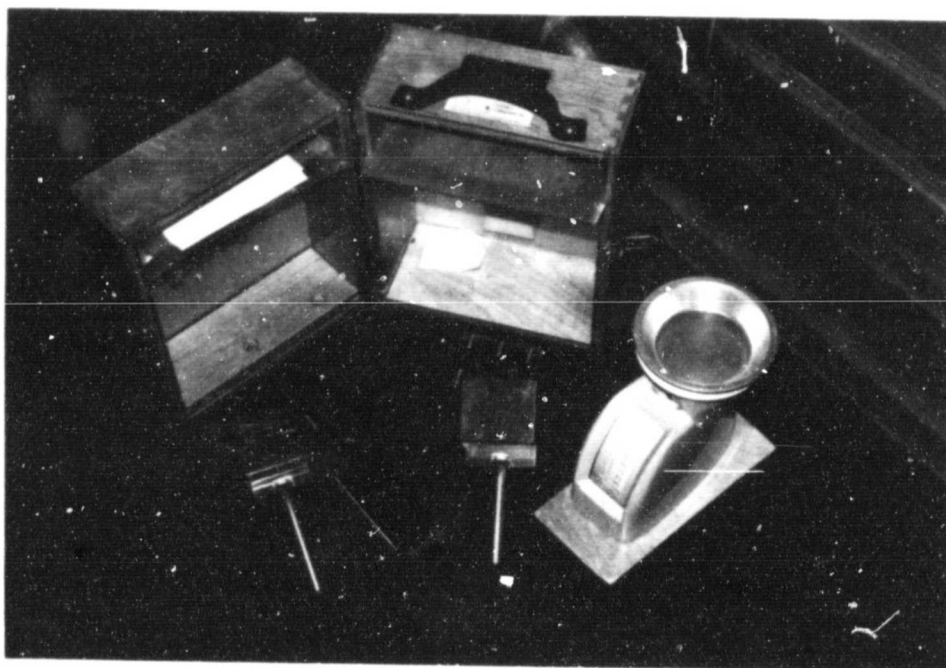


Fig. 7. Portable snow density kit used in snowpits.  
Note the two sizes of rectangular samplers.  
(Resource Consultants, Inc., photo)

Regardless of how density is determined, a careful measurement and documentation system needs to be employed. The record should identify the locations in terms of depth above the soil, ice layers, and other density variations, and should indicate layer density.

Fig. 8 is a plot of typical snow pit data showing graphs of temperature and density profiles and symbols for grain type and hardness along with estimates of grain size. Fig. 9 shows the international nomenclature used for snowpit analysis. (Perla & Martinelli, 1976; Gray & Male, 1981)

If one is caught in the field without such equipment and the need arises to make a snowpit density profile, normally some indication of relative densities can be obtained by merely systematically poking gloved fingers into the snowpack. In relatively low density layers very little resistance will be met whereas in a high density ice layer, no penetration will be possible. Fig. 10 shows a snowpit with observer indicating ice layers.

### Temperature

The measurement of temperature in a snowpack is normally accomplished by using long thin probes which are tipped with either a thermocouple or a thermistor. The probes should be long enough (approximately 30 centimeters), to truly measure the temperature of the snowpack rather than that of the surface or the pit wall. When measuring temperatures in a snow pit, it is suggested that measurements be taken at vertical intervals of approximately 4 to 10 centimeters. This should provide an adequate representation. In snow pits deeper than 1 meter these measurements may be spread out into wider intervals. Properly calibrated glass or metal dial thermometers can also be used, but since the response time is much longer, the time consumed will be much greater. Before going to the field, one should become familiar with the response time of the temperature measuring equipment. If the temperature settles quickly, the probe does not need to be in the snowpack for long. If, however, the response is rather slow, the detailed temperature measurements of the snow pit can be arduous. If one is working in sub-zero temperatures, it is desirable to have a temperature apparatus that will respond quickly to ambient temperatures. Electronic apparatus used in the field to measure temperature must be winterized to prevent failure.

### Snowpit Stratigraphy

When working in a snow pit, one normally tries to sample snow grain sizes and shapes that are present in each of the density layers. To help locate crusts and thin layers, the tip of a small straight edge (e.g., a plastic credit card) can be inserted and moved down the pit wall. This technique is usually helpful in defining stratigraphic layers. Temperature profiles that are taken can give the observer an indication whether TG metamorphism can be expected to intensify in the near future, and can indicate how close the snowpack is to thaw. The temperature of weak layers in the snow can indicate how rapidly the layers will gain strength through ET metamorphism and sintering. When measuring pit wall temperatures a thermometer is placed in the pit wall and given a few minutes to allow the stem to come into equilibrium with the snow. Temperature measurements are usually made at 4 to 10 cm intervals from the top to the bottom of the pack. The use of several thermometers can save considerable time. Fig. 11 shows observers in a snow pit--note the dial type thermometer used to obtain the temperature profile.

The size and shape of ice grains should be determined along with density measurements in each stratigraphic layer. However, for a detailed density profile, it is advisable to take density measurements every 5 cm from the top to the bottom of the pack.

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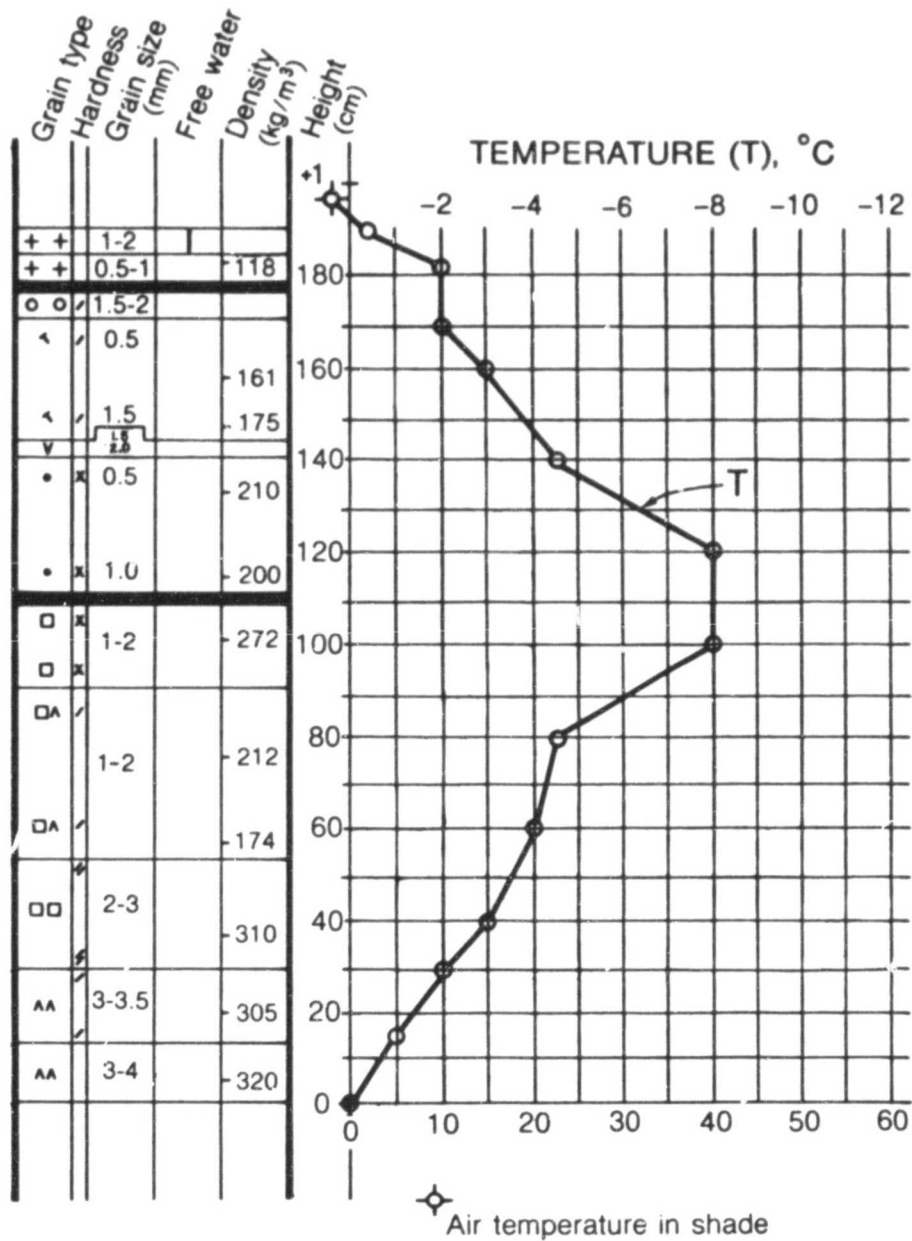


Figure 8: TYPICAL PLOT OF SNOWPIT DATA USING INTERNATIONAL SYMBOLS (Based on Materials from Perla & Martinelli, 1976)

# International symbols and measurements

## Grain type

Symbol	Description
	Freshly deposited snow. Initial forms can be easily recognized.
	Irregular grains, mostly rounded but often branched. Structure often feltlike. Early stages of ET metamorphism.
	Rounded, often elongated, isometric grains. End stages of ET metamorphism. Grains usually less than 2 mm in diameter.
	Angular grains with flat sides or faces. Early stages of TG metamorphism.
	Angular grains with stepped faces; at least some hollow cups. Advanced stages of TG metamorphism.
	Rounded grains formed by MF metamorphism. Grains usually larger than 1 mm and often strongly bonded.
	Graupel. Occasionally appreciable layers of this form of solid precipitation can be identified in the snow cover.
	Ice layer, lens, or pocket.

## Snow surface deposits

Symbol	Deposit	Description
	Surface hoar	Sublimation crystals formed directly on the snow surface.
	Soft rime	White, opaque deposit formed on objects by rapid freezing of supercooled water droplets.
	Hard rime	Formed the same way as soft rime but more compact and amorphous.
	Glazed frost (Verglas or glaze)	Coating of ice, generally clear and smooth but usually including some air pockets formed on objects by freezing of films of supercooled water. Denser, harder, more transparent than rime or surface hoar.

These symbols are also used in snow profiles if the deposits are identified inside the snowpack.

## Hardness

Symbol	Description	Hand test*
	Very soft	Fist
	Soft	Four fingers
	Medium hard	One finger
	Hard	Pencil
	Very hard	Knife
	Ice	—

\* In the hand test the specified object can be pushed into the snow in the pit wall with a force of about 5 kg. In hard snow, for example, a pencil can be pushed into the snow, but with the same pressure, a finger cannot.

## Free water content

Symbol	Term	Description
	Dry	Snow usually, but not necessarily, below 0° C. Grains have little tendency to stick together in a snowball when lightly pressed in gloved hand.
	Moist	Snow at 0° C. No water visible even with hand lens. Snow makes good snowball.
	Wet	Snow at 0° C. Water visible as a meniscus between grains but cannot be pressed out by moderate squeezing in the hand.
	Very wet	Snow at 0° C. Water can be pressed out by moderate squeezing in the hand. There is still an appreciable amount of air confined within the snow.
	Slush	Snow at 0° C. Snow flooded with water and containing relatively small amounts of air.

Fig. 9. International symbols for snowpit data. (Perla & Martinelli, 1976)





Fig. 10. Snowpit with observer indicating ice layers.  
(Photo courtesy of Soil Conservation Service)

One must remember that as soon as the snow pit is dug, snow layers on the pit wall are metamorphosing at a different rate than the normal undisturbed snowpack. Therefore, a fresh face should be scraped in the snow pit for each layer that is being sampled. The pit wall should be extended in the direction of the sun in order to minimize solar radiation reaching the sampling face. This insures a better representation of natural snow conditions than if one merely samples the pit wall exposed to the sun.

In some cases, the classification systems may not be sufficient for characterizing the interaction of electromagnetic radiation with snowpack. A method of profiling grain size with depth by the use of thin-sections has been described by Perla (1982). These measurements are particularly important near the snow surface and are useful when modeling reflection and emission of electromagnetic radiation (Brown et al., 1982).

#### Liquid Water Content

During liquid water content analysis, snow samples should be obtained in much the same manner as those used in observing snow crystal sizes. First a level must be selected at which one wishes to sample. Next, a fresh sample must be obtained by scraping away some material from the pit wall in that zone. The number of zones that are to be sampled for liquid water content will normally be outlined in the ground-truth planning.



Fig. 11. Observers in snowpit. Note the dial type thermometers in the pit wall.

#### Soil Conditions Below the Snowpack

The conditions of the soil beneath the snowpack are often of interest in microwave remote sensing projects. Since the snow itself is a major barrier to obtaining good information on the soil conditions beneath it, one should sample the soil at selected points only. One of the easiest methods of reaching soil is to dig the snow pit all the way through the snow to the soil. If this soil is to be sampled, it should be sampled upon completing the pit because in many winter environments the soil will begin to freeze.

Soil moisture data may be required for given studies. It is suggested that adequate tools for sampling soils be brought along (shovels, trowels, coring tool, etc.). Normally, a minimum of three soil samples taken from the bottom of the pit (each weighing about 200 grams) are adequate for good soil moisture determinations. While digging soil samples, the characteristics of the soil should be carefully noted--plastic, frozen solid, partially frozen, ice crystals, etc.

#### IV. GROUND-TRUTH MISSION ORGANIZATION

##### INTRODUCTION

Now that the reader has an understanding of the amount of work involved in providing adequate ground truth, questions may arise concerning the organization of such an effort. There are no rigid management techniques for operating a ground-truth mission. However, it does take a good understanding of the individual capabilities of the team members to function in a snow environment as well as an understanding of time management and supervision techniques. Finally and most important is a good understanding of what is expected from the ground truth. The variables the ground-truth manager has at his disposal for prioritizing various measurements are (1) changing the time that the measurements are taken, (2) changing the number of measurements in a given spatial area or along a line, and (3) proper utilization of available personnel.

##### PERSONNEL

The personnel selected for a ground-truth team should be chosen on the basis of their ability to contribute to the overall mission of that team. This means that they must be physically and mentally capable of performing the required work in the snow environment and, assuming they are reasonably comfortable in the field, are willing to "give the extra effort" which is often required in ground-truth work. Personnel must also have the necessary safety and survival skills for harsh winter conditions. A team assembled for taking snowpack ground-truth measurements along a flight line might typically consist of approximately six people. This would allow two teams of two each to collect data of depth and density along the flight line, while the other two people dig the snowpit, characterize it, and prepare to take liquid-water content measurements. If another person is available, he may be used as a "rover." The rover continuously checks on various team members by moving along the flight line (if possible) and observing them. The rover is particularly important if radios are not used. However, radios are highly advisable (they must be winterized). If a team were to encounter trouble (breaking a ski, snowshoe, or even a leg, etc.), help would be needed as soon as possible. The rover may also run errands and bring additional food and water or hot drinks to the field.

When working in a fixed spatial area with truck-mounted equipment, normally two or three people are adequate. This situation is usually not so physically demanding as it provides a place to warm up between sample-taking.

##### TRAINING

Members of the team should be trained in field procedures and protocol prior to going to the field on a mission. A great deal of training is normally not required for much of the work on a ground-truth team. Usually an hour or two of work with a snow tube is enough to allow field workers to become sufficiently proficient in its use. An exception is conducting liquid-water determinations using the cold calorimeter.

## EQUIPMENT

Assembling and packing all the equipment necessary for use in the field is a significant task. Once in the field there are often no supply sources. It is recommended that a checklist be methodically prepared and then reviewed by all team members to avoid leaving anything behind. A sample checklist might be as follows:

### Snow tubes

Number of sections

Sharpen the cutter

Spanner wrenches (2)

Scales

Bale for the scales which will hold the snow tube

### Liquid-water content kit (cold calorimeter)

#### Calorimeters

Device for measuring temperatures in the calorimeter and in the snowpack

Will this device work satisfactorily in cold weather?

Are the batteries in this device charged?

Are spare batteries available?

Silicon or other freezing agent in measured quantities stored in a chest

Chest of dry ice which will be adequate to sustain measurements throughout the mission period (or can dry ice be purchased at a site near the flight lines?)

### Vessels for recovering the used silicon fluid

Triple beam scales and weights

### Snowpit kit

Aluminum shovels (2), coal or streetcleaner model

Brush

Folding rule (2 or 3 meters)

Hand lens, plain

Hand lens with reticle (10 mm x 10 mm)

Several dial-stem thermometers or digital readout thermister or thermocouple probes (30 cm or 12 in. in length)

Portable density kit

#### Miscellaneous equipment

30- or 60-meter (100- or 200-foot) cords for measuring distances between depth sampling points

Paper toweling

Flagging to mark points as may be required

First aid kits

Radios (handy talkies, if available)

Will the radios work satisfactorily in cold weather?

Are radio batteries charged?

Are chargers available?

Are extra batteries available?

Shovels

This list is not complete but merely provides an idea of the things to be checked before going into the field. Along with the standard field equipment already mentioned, cross country skis and/or snowshoes for the personnel must be considered. Those taking depth and density data along a flight line or in a large area will normally use cross country skis in order to traverse the area quickly. On the other hand, those working around a fixed site or the snowpit may prefer snowshoes. A field repair kit that includes assorted ski waxes should also be included. For the sake of safety all vehicles should carry adequate chains, small quantities of food, and first-aid kits.

#### TRAVEL

The ground-truth manager must arrange safe and efficient transportation for personnel and equipment. Arrangements must also be made for the necessary transportation needed to move people to various portions of the site study area.

#### ARRANGEMENT FOR ACCESS TO PRIVATE LAND

Arrangements for access (ingress and egress) to the site are a very important part of mission planning. Also obtaining permits or leases may be involved. Normally this is accomplished by the ground-truth manager before the team leaves for the field. However, it is useful to reconfirm the

access once in the field. Often it is possible to work with appropriate governmental agencies in arranging such access. Most landowners will not deny access once the nature of the mission is understood. However, if personnel abuse the land, leave trash, and fail to fill in snowpits, landowners can become irate. Fieldworkers should be as cooperative as possible with landowners.

#### COORDINATION WITH THE REMOTE SENSING AIRCRAFT

The ground-truth manager should also coordinate with the pilot and navigator of the remote sensing aircraft. In some cases the pilot may request that targets be set out at each end of a given line. Targets will normally consist of either very bright orange or black cloth or plastic placed on the ground in a pattern such as a "T" or in a straight line wide enough to be easily seen by the aircraft at their assigned flight level. Experience has indicated, however, that it is often more effective to use ground-to-air communication for direct contact with the pilot so that the pilot can be "talked" to over the line. When this method was used, the writer found it is very effective in keeping the plane on line.

Note: Normally, the pilot will not communicate when taking data over the line, as aircraft radio transmitters may interfere with remote sensing equipment.

#### SAFETY

While it is beyond the scope of this manual to provide a full discussion of snow safety, several points need special emphasis when working in a snow environment.

It must be remembered that it takes longer to complete a task in a cold, hostile environment than in either the laboratory or a warm setting. Special precautions that need to be considered are hypothermia, frostbite, dehydration, and snow blindness. To avoid these problems the best approach is to stay warm and dry. In keeping warm, suitable layers of clothing are needed that can be put on or taken off depending on the level of activity. Care should be taken to avoid excessive sweating which causes excess moisture next to the skin and breaks down the insulating air barrier between one's body and clothing. Specific clothing recommendations will vary with the site, but in general it is preferable to wear clothes that do not absorb and hold moisture next to the skin but are warm and breathable and allow moisture to escape. Wool is by far the preferred material and next are down-filled outer garments. Cotton is not advised. Wearing layered clothing will prevent accumulation of excessive moisture which is the prerequisite to frostbite. Having enough layers will keep the body warm and help prevent hypothermic conditions. Sunglasses with side protectors are recommended to prevent snow blindness. Selected readings on first aid and hypothermia include Thygersen (1982), Parcel (1982), and Edwards (1978).

Safety must be stressed throughout any ground-truth mission because accidents can happen in field work operations. However, when working in the cold and snow, what begins as a minor accident may become very serious if help is not immediately available. Small first aid kits should be carried by each team in the field and a larger kit should be available.

When working in a snow environment, winter squalls and storms can come up rather quickly. Thus, it is the responsibility of the ground-truth team manager to be continually alert for changes in weather forecasts or forecasts of severe winter weather.

Winter temperatures can be cold and when wind is present the wind chill factors can become extreme. It is recommended that ground-truth operations be suspended when the wind chill factor goes down to  $-31^{\circ}\text{C}$  ( $-25^{\circ}\text{F}$ ) or the ambient temperature drops below  $-23^{\circ}\text{C}$  ( $-10^{\circ}\text{F}$ ) (unless arctic gear is furnished to team members and arctic procedures established). Collecting data is not so important that the health and safety of team members should be jeopardized. Wind chill is obtained by establishing both temperature and wind. A wind chill chart is shown in Table 3.

All persons working on a snow ground-truth team must receive proper instruction from competent first aid or medical authorities on how to recognize frostbite and hypothermia. It is the responsibility of each member of the team to watch out for the others as much as possible. Therefore no person should ever go out alone. One final word. All the clothing and equipment that can be carried will be of little value if one is not in reasonably good physical condition.

Table 3  
Wind Chill on Exposed Personnel<sup>1/2/</sup>

Wind speed (mph)	Degrees Fahrenheit											
	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
	(Equivalent temp. ( $^{\circ}\text{F}$ ) created by wind on exposed flesh)											
calm	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
5	43	37	27	16	6	-5	-15	-26	-36	-47	-57	-68
10	40	28	16	4	-9	-21	-33	-46	-58	-70	-83	-95
15	36	22	9	-5	-18	-36	-45	-58	-72	-85	-99	-112
20	32	18	4	-10	-25	-39	-53	-67	-82	-96	-110	-124
25	30	16	0	-15	-29	-44	-59	-74	-88	-104	-118	-133
30	28	13	-2	-18	-33	-48	-63	-79	-94	-109	-125	-140
35	27	11	-4	-20	-35	-49	-67	-82	-98	-113	-129	-145
40	26	10	-6	-21	-37	-53	-69	-85	-100	-116	-132	-148
	Little danger						Great danger					

<sup>1/</sup> There is little additional chilling effect with winds greater than 40 mph.

<sup>2/</sup> The chart is in English units rather than metric, since most weather forecasts in the United States do not give the temperature in degrees Celsius or wind in metric units. The conversions are as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times 5/9$$

$$1 \text{ kilometer/hours} = 0.62137 \text{ miles per hour}$$

## V. REPORTING GROUND-TRUTH DATA

### INTRODUCTION

The final step in ground-truth work is to report clearly and concisely the ground-truth data obtained in the field. Much care is necessary during this phase of the work. Those who will be using the ground-truth data to analyze the remote sensing results will probably not have been in the field and one must assume that the ground-truth team may not be available for further consultation.

### ELEMENTS OF A REPORT

Regardless of the specific format that is used in reporting ground truth, there are certain pieces of information essential to any such report. The first element should be the introduction which includes a summary of the ground-truth data taken, when it was taken, the specific sites involved, and other data pertinent to the mission. It is also advisable to include the names of the personnel who obtained the ground truth. This not only acknowledges their services, but if they need to be contacted later to clarify a point, the analyst will know who was involved. The second element of the report should be a description of the ground-truth site or sites. The general site location or locations should then be indicated on a regional map and on more detailed maps so that the system for numbering samples and measurements can be clearly identified.

Detailed ground-truth data can be presented either in the body of the report or in an appendix. It is preferable to include summaries of the data in the actual report with the detailed data following in a series of appendices. This approach allows the reader to review the report without going through a considerable amount of technical data. It is important, however, to append or include all the data collected. Again, if one is placed in the role of analyst, seemingly insignificant pieces of data may acquire meaning.

Excerpts from a sample report written in connection with an actual snowpack ground-truth mission (April 7-9, 1980) are shown in Appendix C. There is no specific format for these reports, but all essential elements should be included in a readable and workable form.

As a note of caution, the actual field books and all notes taken in the field should be collected by the ground-truth manager as soon as possible to avoid data gaps due to lost notes.



## VI. A LOOK TO THE FUTURE

### INTRODUCTION

The methods discussed in this manual are those that are currently being used. It must be remembered, however, that the concept of formalized ground truth was totally new about 15 or 20 years ago. Techniques are constantly evolving and changing and it is important that those dealing with ground truth look to these new procedures when planning and implementing a ground-truth mission.

### NEW CONCEPTS

One emerging methodology which may be considered is the utilization of various altitudes for data acquisition (i.e., satellite, high flying aircraft, low flying aircraft) in which the remote sensing signatures from these four levels serve as ground truth for each other. That is to say, a low flying aircraft may provide information to a satellite or to a higher flying aircraft. By the same token, a satellite which has a much broader view may provide valuable data which can serve as ground truth for the low flying aircraft.

New techniques are also being developed in specific measurements. The new metric snow tube will soon be introduced for use on western snowpacks. Because of its increased accuracy it should be used in ground-truth missions as soon as it becomes available. New methods are also being developed to observe liquid-water content determinations. These will be either a capacitance measurement, an FM-CW type scan through the snowpack using two wave lengths (Ellerbruch & Boyne 1980), or the new technique being proposed by CRREL that determines liquid water by melting snow samples in an alcohol solution held at 32°F (0°C).

The incorporation of these new techniques will not necessarily happen overnight. They must be tested and, once tested, should be run parallel with existing techniques, so that relative errors or differences can be adequately assessed. The metric snow tube is an excellent example of testing new equipment. When considering new concepts in ground truth it should be remembered that the purpose of ground truth is to collect data which is helpful in analyzing remote sensing signatures. It is not necessarily a testing ground for new techniques. The most effective, proven, and time efficient techniques should be used in the field. It is also important to have any new technique approved by the mission technical manager before use in the field.

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## APPENDIX A

### COLD CALORIMETER ANALYSIS

This material is a revised and condensed version of a report entitled "Measurement of Liquid Water Content in a Melting Snowpack Using Cold Calorimeter Techniques," by E. Bruce Jones, Resource Consultants, Inc.; Albert Rango, Goddard Space Flight Center; and Steven Howell, Resource Consultants, Inc., which appears in the Conference Proceedings published by the National Aeronautics & Space Administration in 1980 as NASA Conference Publication 2153--Microwave Remote Sensing of Snowpack Properties.

The basic equation for cold calorimetry is shown below:

$$Q_f = 1 - \left[ \frac{[(W_2 - W_1) + E] (t_2 - t_1) C_f}{L(W_3 - W_2)} - \frac{C_1(t_3 - t_2)}{L} \right] \quad (A-1)$$

Where

$Q_f$  = snow quality in percent

$E$  = calorimeter constant in gms

$L$  = latent heat of fusion in cal/gm

$C_f$  = specific heat of freezing agent at  $\frac{t_1 + t_2}{2}$  in cal/gm/°C

$C_1$  = specific heat of ice at  $\frac{t_2 + t_3}{2}$  in cal/gm/°C

$W_1$  = tare weight of calorimeter in gms

$W_2$  = weight of calorimeter and freezing agent in gms

$W_3$  = weight of calorimeter, freezing agent and snow in gms

$t_1$  = initial temperature of the freezing agent in °C

$t_2$  = final temperature of freezing agent and snow mix in °C

$t_3$  = initial temperature of the snow at sample point

It should be noted that the percent of liquid water content =  $1 - Q_f$ .

#### COLD CALORIMETER EQUIPMENT AND PROCEDURES

##### FIELD EQUIPMENT

Listed below is the basic equipment required for utilizing the cold calorimeter technique in the field.

- Calorimeter. For this experiment, the calorimeter was constructed from a wide mouth vacuum bottle made of stainless steel.
- Scales. The scales should be capable of weighing up to 2,000 grams and should be readable to the nearest tenth of a gram.

• Temperature Probes. Various types are available and can be used, but they should be easily read and of a design that allows for field use. In this experiment, 12-inch stainless steel thermocouple probes were used. A multi-channel digital readout was employed so that air and snowpack temperatures could be read simultaneously.

In addition to these basic requirements, several other items of equipment are necessary:

- Cold chest for storing the freezing agent
- Thermal containers for obtaining the snow samples
- Timing devices
- Miscellaneous tools such as shovels, trowels, spoons, etc.

Fig. A-1 shows the calorimeter with the temperature probe. Fig. A-2 shows the typical equipment used for field operations in the back of a four-wheel-drive support vehicle. Fig. A-3 shows the field facility in operation at the 1979 test site near Fraser, Colorado.

#### FREEZING AGENTS

Cold calorimetry requires the use of a freezing agent to freeze the liquid water in the snow sample. Some very small portions will not be frozen, but the resulting error is considered to be negligible.

Ideally, a freezing agent should have low viscosity (down to about  $-60^{\circ}\text{C}$ ), high flash point, be easily obtainable and non-toxic. Also, it is desirable that the freezing agent leave no residue or film in the calorimeters.

Because of safety considerations, a very light silicon oil was tested for use as a freezing agent. The specific substance used was General Electric SF-96-5.<sup>1/</sup> This product is more expensive and requires careful cleaning of equipment; but, because of the safety gained, it is considered superior to toluene. The specific heat of the silicon fluid can be found in Table A-1.

Part of the additional expense of silicon can be offset by the fact that much of it is reclaimable. Let the ice silicon mixture warm so that all the ice is melted. The water can then be removed and the silicon filtered. Only a small portion of the silicon is lost.

#### CALORIMETER CONSTANT DETERMINATION

The determination of snow liquid water content through the use of the freezing calorimetry involves a heat-balance relationship that occurs between a freezing agent and the liquid water in a snow sample when mixed

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<sup>1/</sup>The use of a trade name in no way implies endorsement. The specific name is given so that the reader may investigate its properties.



together in a closed container. The type of container which is generally used for the mixing process is a vacuum insulated bottle with a temperature probe and a tightly fitted rubber stopper. Experience indicates that a commercial, 0.946 liter (1-quart), stainless steel, wide-mouth vacuum bottle works quite well. The temperature probe is used to monitor changes in temperature that occur in the vacuum bottle during the mixing process. The heat-balance equation is dependent upon accurate measurements of temperature changes occurring inside the bottle during a typical mix. Knowing that the vacuum insulated bottle is not a perfect system and that some heat will be gained by the bottle itself, the heat-balance equations (Equations 1 and 2) contain a calorimeter constant, E. Each individual calorimeter bottle will have its own constant and must be determined independently. For convenience when using heat-balance equations, the calorimeter constant is expressed in terms of equivalent weight of freezing agent. Various methods may be used to determine this constant. This discussion considers only the method developed in the course of this study.

References are made throughout this discussion to the typical calorimeter constant determination shown in Fig. A-4. This determination was only one in a series of twelve used to obtain an adequate sample from which the mean value for a specific calorimeter bottle was computed. The freezing agent used was a silicone fluid. The calibration of the calorimeter bottle was done in the laboratory using the same equipment used in actual field operations. Quantities and time frames were approximated to match those used in field procedures. Temperatures were varied from run to run to simulate changing field conditions.

### Theory

The calorimeter constant is determined by a basic heat-balance equation. When a warm fluid is mixed with a cold fluid in a calorimeter bottle, the heat which is lost by the warm fluid must be equal to the heat gained by the cold fluid and the bottle itself. The heat-balance equation is:

$$\frac{\text{Heat lost by warm fluid}}{\left[ Wt_{\text{warm}} \right] \left[ \frac{Cs_w + Cs_2}{2} \right] \left[ T_w - T_2 \right]} = \frac{\text{Heat gained by cold fluid + bottle}}{\left[ Wt_{\text{cold}} + E \right] \left[ \frac{Cs_1 + Cs_2}{2} \right] \left[ T_2 - T_1 \right]}$$

where

$Wt_{\text{warm}}$  = Weight of warm fluid

$Wt_{\text{cold}}$  = Weight of cold fluid

E = Calorimeter constant expressed in equivalent grams of fluid

$T_w$  = Initial temperature of warm fluid before mixing

$T_1$  = Initial temperature of cold fluid before mixing

$T_2$  = Final temperature of warm-cold fluid mix

$Cs_w$  = Specific heat of fluid at temperature of warm fluid

$Cs_1$  = Specific heat of fluid at temperature of cold fluid

$Cs_2$  = Specific heat of fluid at final temperature of mix

The fluid weights are directly obtainable and can be determined with reasonably high accuracy. Also, the specific heats of the fluid can be obtained directly from charts after the corresponding temperatures have been determined. Table 1 shows the specific heat values for the silicon oil used. The determination of the initial and final temperatures of the fluid is the most critical and time-consuming part of the process. These determinations are also the greatest potential source of errors in the system. The temperature values are determined by standard calorimeter techniques which involve the extrapolation of temperature curves. The cold fluid (approximately 1 pint) is poured into the calorimeter bottle (a 0.946 liter [1 quart] size vacuum insulated bottle) at time zero. The initial warm up of the fluid and cooling of the bottle occurs in the first 3 minutes. Then the slope of the temperature curve becomes fairly uniform indicating that the bottle itself has cooled and is now gaining heat from the outside through the walls at an almost constant rate. The temperature of the fluid is monitored for 8 minutes to get a good definition of the slope of the curve. In the period between 8 and 9 minutes the warm fluid (approximately  $\frac{1}{2}$  pint), with a measured temperature of  $T_w$ , is added and mixed thoroughly. Temperature recordings are begun at the 9-minute mark and are recorded until the slope of the second curve stabilizes and becomes relatively constant (about 5 minutes). Note that the bottle should be shaken lightly during the entire period to insure uniform temperatures throughout the interior of the bottle and the fluid. The curves are plotted as shown in Fig. A-4 and both are extrapolated to the mid-point in time (8.5 min.) when the transfer of heat during the mix should occur. The initial ( $T_1$ ) and final ( $T_2$ ) temperatures can be picked off the curves with reasonable accuracy. The calorimeter constant can then be calculated as shown at the top of Fig. A-4.

### Results

When the calibration of a calorimeter bottle is performed under laboratory conditions, the accuracy of the measuring equipment and the technique and experience of the calibrator will determine the precision and repeatability of the results. Accurate scales and temperature measurements will eliminate errors in the actual data taking. However, plotting and interpretation of temperature data can be a source of error that is difficult to eliminate. Thus, in practice the authors have used an average of 10 to 12 calibrations in determining the calorimeter constant. The heat-balance equation is quite sensitive to the two temperature factors. Therefore, the plotting of temperature curves and the extrapolation of the slopes to the required points should be done carefully. Actual laboratory procedures using a beam scale accurate to 0.1 gram and an electronic digital thermometer accurate to 0.1 degree centigrade have produced sets of calorimeter constants of 12 values that are within 10 percent of the mean value. This range of values is within the limits of the system.

### FIELD PROCEDURE

The freezing agent is stored in 1-pint glass bottles and placed in an insulated ice box containing dry ice. The temperature of the freezing agent is maintained from  $-40^{\circ}\text{C}$  to  $-50^{\circ}\text{C}$ . It is important to maintain this range of temperature, particularly during periods of high air temperature and high liquid water content in the snowpack so that the resultant tempera-

ture,  $t_2$ , will be less than  $0^\circ\text{C}$ . The calorimeter is pre-cooled to the average internal operating temperature prior to taking the first set of data. During actual measurements, the calorimeter will remain cool due to the freezing agent. After the calorimeter bottle has cooled for approximately 20 minutes (the average time per run) using 1-2 pints of freezing agent, the bottle is emptied, wiped dry, and a tare weight ( $W_1$ ) is obtained. One pint of freezing agent is then poured into the bottle and the cap is sealed on. At this point the total weight of the bottle and freezing agent ( $W_2$ ) is obtained and recorded. Investigation of standard calorimetric techniques has led to obtaining an initial temperature ( $t_1$ ) for the freezing agent through extrapolation of a temperature curve in the same manner as that used for calorimeter constant determination (see Fig. A-4). The temperature of the freezing agent is monitored and recorded every 30 seconds while the bottle is shaken. After the first 3-5 minutes of shaking, the slope of the temperature curve becomes fairly uniform. The temperature monitoring is continued for 8 minutes in order to get a good definition of the slope of the curve. A pre-cooled thermos bottle is used to collect and store the snow sample to transfer it to the field laboratory site. The snow (approximately 200-225 grams) is then added to the cold freezing agent in the calorimeter and the cap is sealed on again. The bottle is shaken thoroughly to mix the contents. The procedure calls for monitoring temperatures again in 30-second intervals until the temperature curve becomes well defined (about 4-5 minutes). The total weight of the bottle, freezing agent, and snow ( $W_3$ ) is measured and recorded to complete one phase of the routine. The procedure is dependent on maintaining a good record of time throughout the entire process. The initial temperature curve is obtained from observations taken every 30 seconds during the 0-8 minute interval. The snow is added between minutes 8-10. Mixing takes place during the interval between minutes 10-14, and a second temperature curve is obtained from every 30-second observation made during this time. Both temperature curves are extrapolated to the 9-minute point at the moment when the transfer of heat during the mix is assumed to occur. At this point the temperatures  $t_1$  and  $t_2$  are determined from the two curves as indicated in Fig. A-4. The field procedures used in the 1976 and 1979 measurements are similar in time frames and general methods. The field procedure for the 1979 measurements has been refined through the use of more precise measuring equipment and basic refinement of the calorimeter technique itself.

Operating cold calorimeter apparatus under winter field conditions leads to difficulties when weighing samples and measuring temperatures. Scales and temperature systems should be checked for accuracy prior to field operations in order to minimize basic calibration errors.

Fig. A-5 shows the form on which data are recorded, for the liquid water analysis using the cold calorimetric technique. The example form illustrates typical values one might expect in working with a moderately wet snow. Fig. A-6 shows the graphical determination of  $t_2$  and  $t_1$ .

#### DATA PRESENTATION

Examples of freezing calorimeter results are shown in Table A-2 and Fig. A-7.

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Table A-1

Specific Heat of Silicone Fluid  
(General Electric SF - 96 - 5)

<u>t</u> <u>°C</u>	<u>Cs</u> <u>Cal/g/°C</u>
10	.4412
0	.4393
-10	.4375
-20	.4356
-30	.4337
-40	.4318



Fig. A-1. Calorimeter Bottle with Temperature  
Probe and Rubber Stopper

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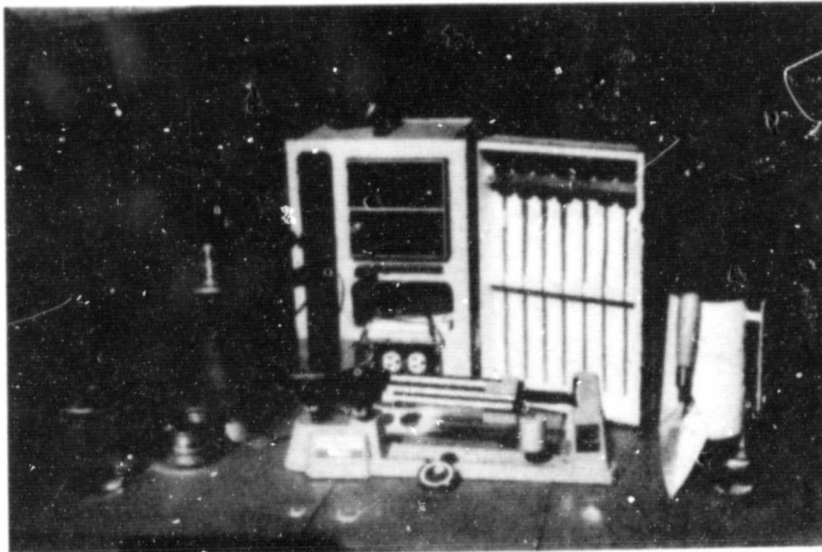


Fig. A-2. Cold calorimeter equipment set including calorimeter bottle, digital readout for temperature probes, thermos bottle for collection of samples, scales, trowel and spoon, temperature probes, clock, stopwatch, and container of freezing agent.

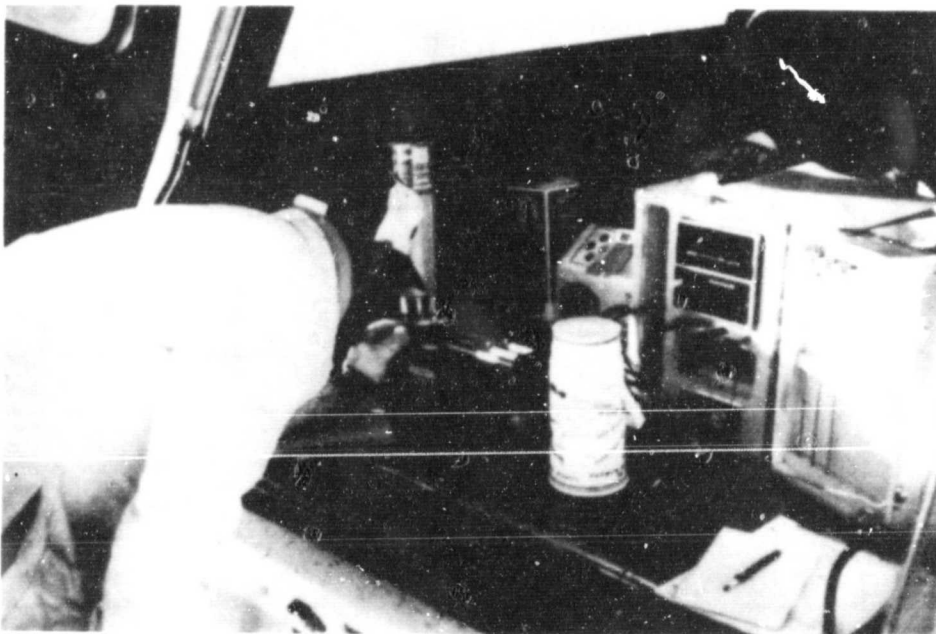


Fig. A-3. Calorimeter field facility in operation near Frazer, Colorado.

TARE WT. OF BOTTLE = 1040.0g  
TARE WT. + COLD SILICONE = 1371.7g  
TARE WT. + COLD + WARM SILICONE = 1478.4g

Wt. cold = 331.7g  
Wt. warm = 106.7g

$T_w = +7.6^\circ\text{C}$

$$(W_{\text{warm}}) \left( \frac{C_{\text{W}} + C_{\text{S2}}}{2} \right) (T_w - T_2) = (W_{\text{cold}} + E) \left( \frac{C_{\text{S1}} + C_{\text{S2}}}{2} \right) (T_2 - T_1)$$

$$(106.7g) \left( \frac{.4373}{2} \right) (37.6^\circ) = (331.7g + E) \left( \frac{.4328}{2} \right) (9.7^\circ)$$

$$\underline{\underline{E = 86.2g}}$$

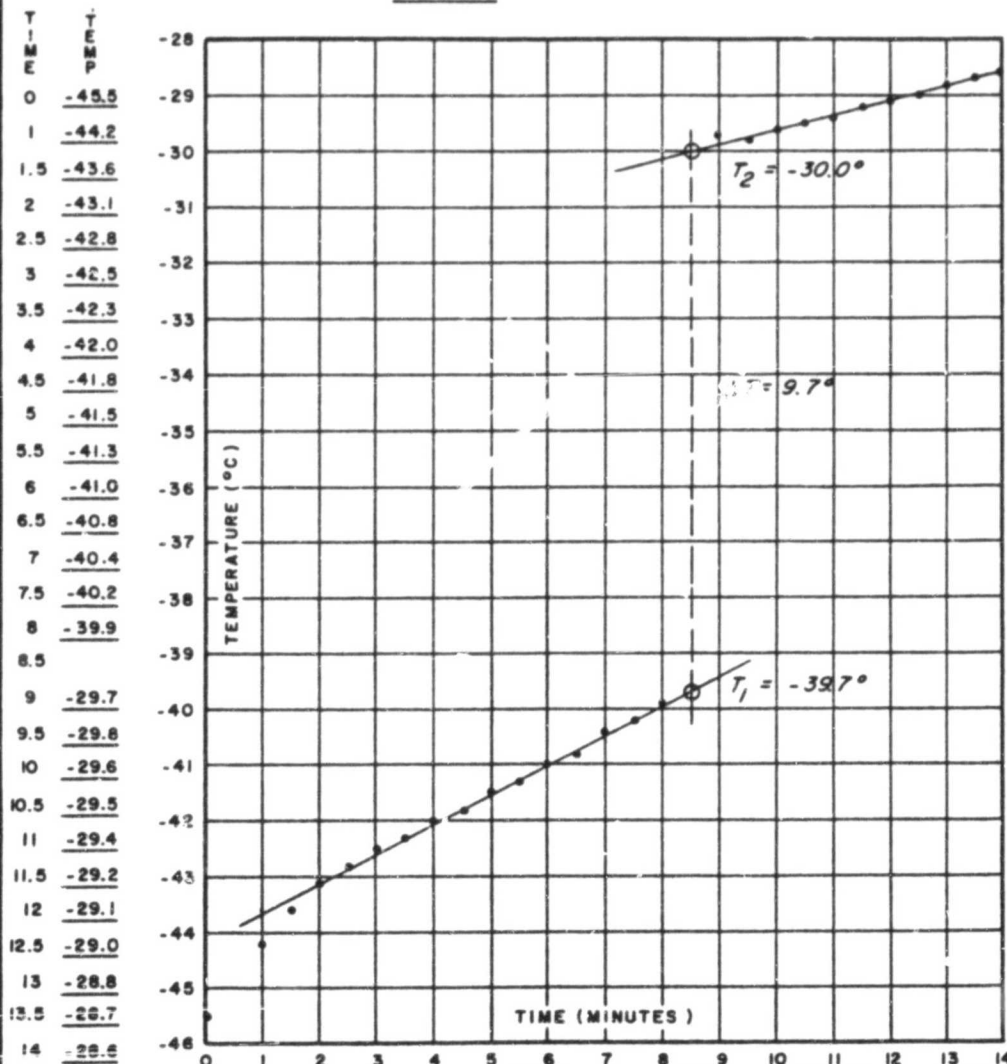


Fig. A-4. Typical calorimeter constant calculation.

MEASUREMENT OF SNOW QUALITY  
(Freezing Calorimetric Technique)

Time	Temp °C	Station	Fraser Valley	Observer	SH
0	-58.5	Date	3/15/79	Hour	1221
1	-55.3	Location and description of sampling point			
1.5	-54.2	Top 4 cm of snow at Fraser Valley Snow Pit			
2	-53.3				
2.5	-52.3				
3	-51.4				
3.5	-50.6				
4	-49.8				
4.5	-49.1				
5	-48.3				
5.5	-47.6				
6	-46.8				
6.5	-46.1				
7	-45.5				
7.5	-44.8				
8	-44.2				
8.5					
9					
9.5					
10	-26.4				
10.5	-24.1				
11	-23.6				
11.5	-23.3				
12	-23.0				
12.5	-22.7				
13	-22.4				
13.5	-22.1				
14	-21.8				
14.5					
15					
15.5					
16					
16.5					
17					
17.5					

Data

Sample thermos No. 105 Air Temperature +4.0 °C

Height of sample from ground surface 34.5 inches.

(1) Tare weight of calorimeter 1261.5 gr. ( $W_1$ )

(2) Weight of calorimeter and silicone fluid 1651.5 gr. ( $W_2$ )

(3) Weight of calorimeter + silicone fluid + snow 1826.3 gr. ( $W_3$ )

(4) Calorimeter constant (E) 92.2 gr.

(5)  $t_1 = -42.9^\circ$   $t_2 = -24.8^\circ$   $t_3 = 0^\circ$

(6) (2) - (1) = 390.0 gr.

(7) (3) - (2) = 174.8 gr.

Snow Quality

$$Q'_f = 1 - \frac{[W_1 C_f (t_2 - t_1) - C_1 (t_2 - t_3)]}{LS} = 0.879$$

$$\% \text{ free water} = 100 (1 - Q'_f) = 12.1\%$$

where

$W_1 = W_2 - W_1 + E$ , gr.

$C_f$  = specific heat of freezing agent at average temp.  $\frac{(t_1 + t_2)}{2}$

$C_1$  = specific heat of ice at average temp.  $\frac{(t_2 + t_3)}{2}$

$S = W_3 - W_2$ , gr.

$L$  = latent heat of melting

$t_1$  = initial temp. °C  
 $t_2$  = final temp. °C  
 $t_3$  = snow temp. °C

RCI form # 751-A  
1-79

Fig. A-5. Data form for calculation of snow quality and liquid water content with data taken at the Frazer Valley site at 1221 hours on March 15, 1979.

Table A-2. COLD CALORIMETER DATA FOR LIQUID WATER CONTENT DETERMINATIONS AT  
VARIOUS LAYERS IN THE SNOWPACK ON MARCH 30, 1979 AT THE  
STEAMBOAT SPRINGS SITE.

Depth	Time	Air temp abd sun	E (g)	W <sub>1</sub> (g)	W <sub>2</sub> (g)	W <sub>3</sub> (g)	T <sub>1</sub> (°C)	T <sub>2</sub> (°C)	T <sub>3</sub> (°C)	Q <sub>f</sub>	Liquid water (%/100)	Oper.	Remarks
0-6cm	0846	1.8 0.4	92.2	1351.1	1754.2	1812.6	-43.6	-38.1	0	.9719	.0281	HU	Partial overcast, winds calm
	0848	2.0 2.8	78.7	1320.0	1722.3	1787.1	-54.5	-46.7	0	.9586	.0414	SH	Sunny, calm
	0913	0.8 6.1	92.2	1351.9	1736.2	1812.0	-44.7	-36.5	0	.9367	.0633	HU	Sunny, calm
	0917	0.8 6.1	78.7	1320.4	1709.6	1800.3	-60.8	-48.6	0	.9421	.0579	SH	Sunny, calm
6-12cm	0943	0.7 9.1	92.2	1352.2	1762.1	1924.2	-45.4	-31.4	0	.9524	.0476	HU	Partly cloudy, calm
	0946	0.8 5.3	78.7	1321.0	1697.8	1895.5	-60.1	-37.4	0	.9386	.0614	SH	Partly cloudy, calm
12-23cm	1010	1.6 5.3	92.2	1351.7	1760.5	2017.2	-40.2	-18.4	0	.8812	.1188	HU	Overcast, calm
	1015	2.9 4.4	78.7	1321.0	1712.4	2000.0	-59.2	-29.5	0	.9144	.0656	SH	Overcast, calm
24-60cm	1037	5.8 5.1	92.2	1351.8	1735.4	1876.2	-46.2	-24.4	0	.8577	.1423	HU	Overcast, calm
	1044	2.9 7.2	78.7	1320.0	1682.0	1851.8	-52.7	-29.8	0	.8570	.1430	SH	Partial overcast, calm
60-70cm	1108	5.6	92.2	1351.9	1760.0	1920.8	-37.7	-23.1	0	.8932	.1068	HU	Partly cloudy, sunny, calm
	1113	5.8	78.7	1321.6	1717.8	1914.7	-52.6	-30.9	0	.9015	.0985	SH	Partly cloudy, sunny, calm
0-6cm	1134	4.6 4.4	92.2	1351.5	1722.4	1838.0	-36.7	-19.9	0	.7557	.2443	HU	Partly cloudy, sunny, calm
	1139	4.3 6.4	78.7	1320.7	1698.1	1821.6	-53.3	-31.1	0	.7428	.2572	SH	Partly cloudy, sunny, calm
0-6cm	1158	3.0 8.5	92.2	1352.5	1711.6	1877.6	-36.7	-14.7	0	.7652	.2348	HU	Sunny, calm
	1200	3.0 8.5	78.7	1321.4	1700.1	1844.7	-53.5	-26.7	0	.7025	.2975	SH	Sunny, calm

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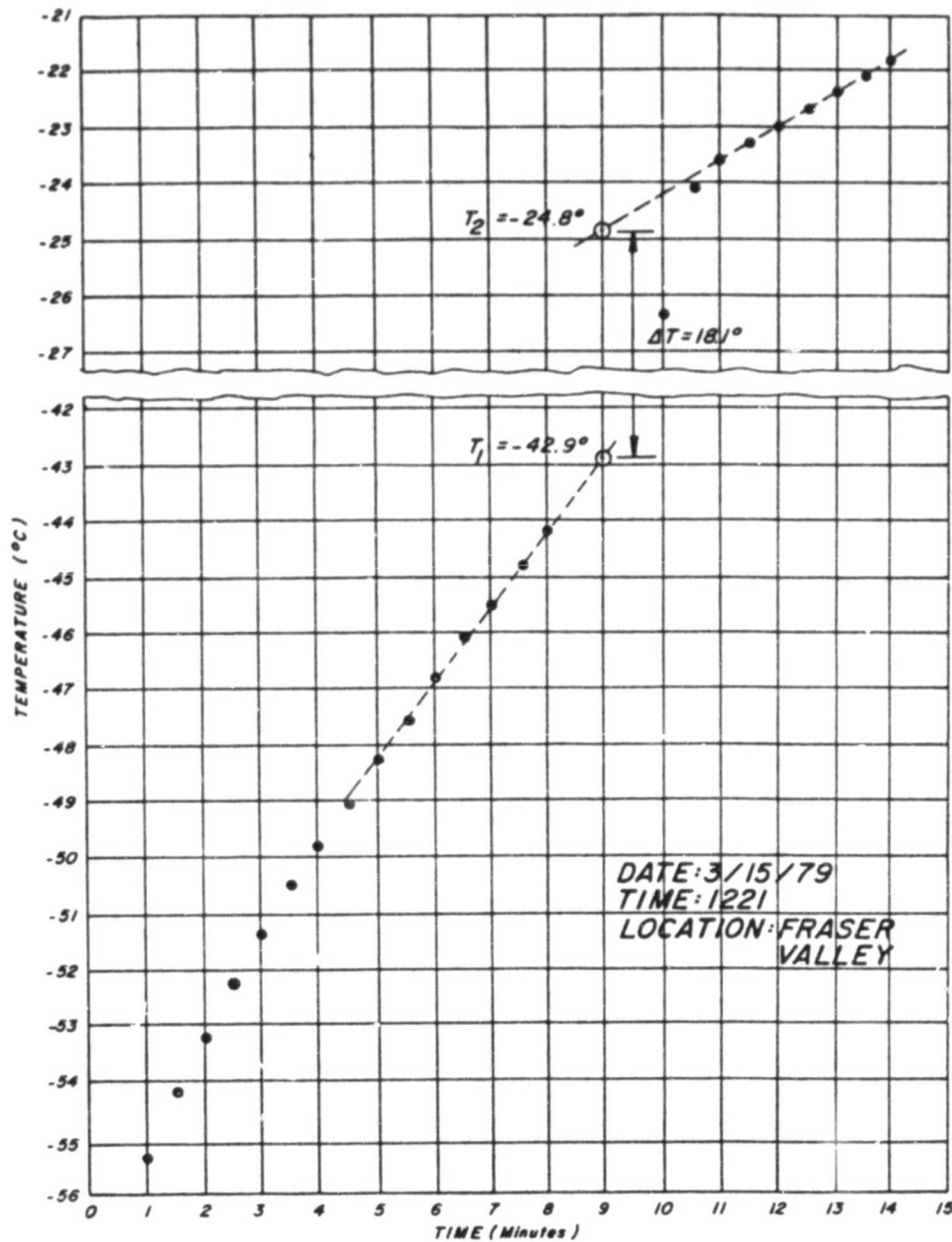


Fig. A-6. Graphical determination of  $t_1$  and  $t_2$  at the Frazer Valley site at 1221 hours on March 15, 1979.

APPENDIX B

Classification Outline for  
Snow on the Ground

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U.S.D.A. Forest Service Research Paper RM-48 1969  
Reissued June 1976

Classification  
Outline  
for

SNOW  
ON THE  
GROUND

R. A. Sommerfeld

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Forest Service U.S. Department of Agriculture  
Fort Collins, Colorado 80521

(Used with permission of Rocky Mountain Forest and Range  
Experiment Station)

**—About the cover:**

**Stage II.A.1. The beginning of equi-temperature metamorphism when the original snow crystals begin to lose their fine detail.**

U.S.D.A. Forest Service  
Research Paper RM-48

1969

**Classification Outline for Snow on the Ground**

by

**R. A. Sommerfeld, Associate Geologist  
Rocky Mountain Forest and Range Experiment Station<sup>1</sup>**

<sup>1</sup>Central headquarters maintained at Fort Collins in cooperation with Colorado State University.

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Decreasing grain size	
Beginning . . . . .	II.A.1.
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Increasing grain size	
Beginning . . . . .	II.B.1.
Advanced . . . . .	II.B.2.
Temperature-gradient metamorphism	
Early	
Beginning . . . . .	III.A.1.
Partial . . . . .	III.A.2.
Advanced . . . . .	III.A.3.
Late	
Beginning . . . . .	III.B.1.
Advanced . . . . .	III.B.2.
Firnification	
Melt-freeze metamorphism	
Limited . . . . .	IV.A.1.
Advanced . . . . .	IV.A.2.
Pressure metamorphism	
Beginning . . . . .	IV.B.1.
Advanced . . . . .	IV.B.2.

# Classification Outline for Snow on the Ground

## Definitions

Terms which are commonly used in snow research are listed here with their definitions. We hope that by defining these terms we will avoid the confusion which has resulted from their misuse.

**Angular grain:**

A grain with facets which are separated by sharp corners.

**Crystal:**

Any substance, usually solid, whose atoms or molecules are arranged in an orderly array.

**Cup crystal:**

A snow grain with a roughly pyramidal shape and a roughly hexagonal cross section. The surfaces of cup crystals are usually deeply stepped. The cups may be filled or hollow.

**Deposition:**

The direct formation of ice from the vapor phase.  
The opposite of sublimation.

**Facet:**

A plane or flat surface on a grain. These are usually external manifestations of the internal order of a crystal.

**Form:**

The external shape of a crystal, which may or may not reflect its internal order.

**Grain:**

The obvious subunit in snow on the ground. In snow research, this term does not have the same meaning as the term in metalography.

**Lattice grain:**

A grain of irregular form with pronounced stepped surfaces.

**Neck:**

The narrow interconnections between grains or parts of grains.

**Phase:**

A system that is uniform throughout, both in chemical composition and physical state (neglecting the effects of surface energy).

**Pore:**

The spaces in a solid material which are not occupied by a solid. These may interconnect so that a fluid can pass through a sample of the material, or they can be noncommunicating so that the material is impervious to fluids.

**Precipitation:**

Liquid or solid water that falls from the atmosphere to the ground.

**Snow crystal:**

A single crystal of ice, usually of complex form, which grows by vapor deposition in the atmosphere.



**Snowflake:**

A polycrystal of airborne snow. An agglomerate of snow crystals.

**Structure:**

1. The arrangement of atoms in a crystal.
  2. The layering or stratigraphy of a snow cover.
- Because of the vast difference in scale, there should be no confusion over the two meanings.

**Sublimation:**

The process of vapor forming directly from a solid.  
The opposite of deposition.

**Surface energy:**

The energy required to form a certain amount of new surface, for example between ice and air.

**Texture:**

The relationships among snow grains or crystals in a snow cover.

## **Discussion**

Previous classification schemes for deposited snow have been based primarily on the forms of the snow grains. Such a basis was necessary when little was known about the processes which occur during the metamorphism of a snow cover. Recent work has outlined the important processes and their relationships to the various forms, so that it is now possible to develop a classification scheme based on physical processes. Since these processes are directly related to the

changes in the physical properties of a snow cover, such a classification scheme will be more useful in evaluating these properties. Also, by systematizing the processes, a better understanding of their relationships can be gained and areas where more work is needed will be made apparent.

In the following classification for snow on the ground, we have separated and idealized the important processes in snow metamorphism. Snow found in nature will undergo some mixture of the processes listed, and its history could be summarized by a series of classifications. Words to be found in the list of definitions are in bold type. The illustrations that follow are keyed into the classification system.

## **Classification**

### **I. UNMETAMORPHOSED**

The major process that affects snow as it precipitates is mechanical breakage under wind action.

#### **A. No wind action**

Since this snow is not strongly affected by any process, there is little difference between it and snow in the air. We recommend, therefore, that it be classified in accordance with the system of Magono and Lee (1966).

#### **B. Wind blown**

Snow in this classification contains very few, if any, whole snow crystals. Parts of the original

forms may be recognizable, or the process may have proceeded to the point that no forms can be recognized. We also recommend the system of Magono and Lee (1966) for this category.

#### **C. Surface hoar**

The deposition of water vapor directly on the surface without precipitation. The forms are similar to those developed under III B (below) except that flat plates are much more common, and there is no pronounced three-dimensional development.

### **II. EQUI-TEMPERATURE METAMORPHISM**

The process that distinguishes this category is the transport of water vapor from regions of high surface energy to regions of lower surface energy in a snow cover which has a constant, below freezing, temperature throughout. This process leads to the destruction of the original forms and to the production of uniform, fairly well-rounded grains.

#### **A. Decreasing grain size**

The destruction of sharp corners, the pinching off of necks, and the thickening of plates while their major diameter decreases, leads to a decrease in apparent grain size.

##### **1. Beginning**

Many of the original snow crystal shapes are recognizable but sharp corners have been rounded and most of the fine structure of the snow crystals has disappeared.

## **2. Advanced**

A very few indistinct plates or snow crystal fragments may be recognizable, but the grains show distinct rounding.

### **B. Increasing grain size**

For grains of the same shape, the smaller the size the larger the ratio of surface area to mass. Therefore, surface energy decreases further as the smaller grains disappear and the larger grains grow. This leads to an increase in average grain size and a decrease in grain number.

### **1. Beginning**

No original snow crystal forms may be recognized. The grains show a definite equidimensional tendency. A few, indistinct facets may be visible.

### **2. Advanced**

Larger, more equidimensional grains characterize this snow. There is a strong tendency toward uniform grain size, and faceting is generally absent.

## **III. TEMPERATURE-GRADIENT METAMORPHISM**

Under a strong temperature gradient, water vapor is transported from the warmer (lower) to the colder (upper) layers by sublimation and deposition.

The relatively rapid transport of water vapor causes the lower portions of each grain to be in a supersaturated environment while the upper portions are in an undersaturated environment. The water vapor sublimates from the tops of the grains and deposits on the bottoms of grains above. The final result is well-oriented grains whose form reflects the temperature and vapor pressure gradients. Stepped surfaces, which are a known feature of rapid growth from the vapor, characterize most of the snow in this category.

#### **A. Early**

The result of a strong thermal gradient on new-fallen snow, usually associated with the first snowfalls of the season. Since the starting material has a large number of small grains, the very large, well-developed cups and lattice grains will not form.

##### **1. Beginning**

Angular and faceted grains are common, but stepped surfaces are very uncommon.

##### **2. Partial**

Medium-size angular grains predominate. Poorly formed steps are commonly found.

##### **3. Advanced**

Medium to large angular grains predominate, with well-developed facets and stepped surfaces. A few filled cups or an occasional hollow cup may be found.

## **B. Late**

The result of a strong thermal gradient acting on snow in the later stages of metamorphism. Because the initial grains are relatively large and few in number, vapor transport produces larger, very well-developed cups and lattice grains. There may be some overlap with category III-A.

### **1. Beginning**

Medium to large angular and faceted grains predominate. Fairly well-developed stepped surfaces are common.

### **2. Advanced**

Large and very large grains predominate. Very fragile hollow cups and lattice grains with very well-developed stepped surfaces are common.

## **IV. FIRNIFICATION**

Equi-temperature metamorphism leads to some densification of the snow cover. However, once the density has reached approximately that of randomly packed, uniform ice spheres ( $580\text{-}600\text{ kg/m}^3$ ) further densification occurs through other processes. The two most important processes are melting and refreezing, and the reduction of pore space by relatively high pressure.

## **A. Melt-freeze metamorphism**

When the snow temperature reaches the freezing point, either because of warm air temperatures or because of high solar radiation, the snow begins to melt and becomes a two-phase mixture. The melt water is trapped between the grains, filling some of the pore spaces. Refreezing then results in a denser snow cover. Polycrystalline grains characterize this sub-category.

### **1. Limited**

The result of a single melt-freeze cycle with a limited gain in density. This causes thin ice layers and ice lenses in the snow cover when subsequent precipitation buries the layer.

### **2. Advanced**

Repeated melt-freeze cycles result in an appreciable gain in density and an increased mechanical strength. The density range in this category is 600-700 kg/m<sup>3</sup>.

## **B. Pressure metamorphism**

The second important process in the densification of the snow cover is the reduction of pore space through action of pressure. This process is important in the formation of glacier ice from snow. Polygranular crystals are found almost exclusively in this sub-category.

## **1. Beginning**

The grains are visibly deformed and rearranged by pressure. The pore space is reduced but is still communicating, and the density range is 700-800 kg/m<sup>3</sup>.

## **2. Advanced**

The grains are deformed and pressed together so that the pore space becomes noncommunicating (the permeability becomes zero). The density range is 800-830 kg/m<sup>3</sup>.

## **Recommended Reading**

Knight, Charles A.

1967. The freezing of super cooled liquids. Van Nostrand Momentum Book 14, 145 pp., illus. Princeton, N. J.: D. Van Nostrand Co., Inc.

LaChapelle, Edward R.

1969. A field guide to snow crystals. Seattle: Univ. Washington Press. (In press.)

\*Magono, Choji, and Lee, Chung Woo

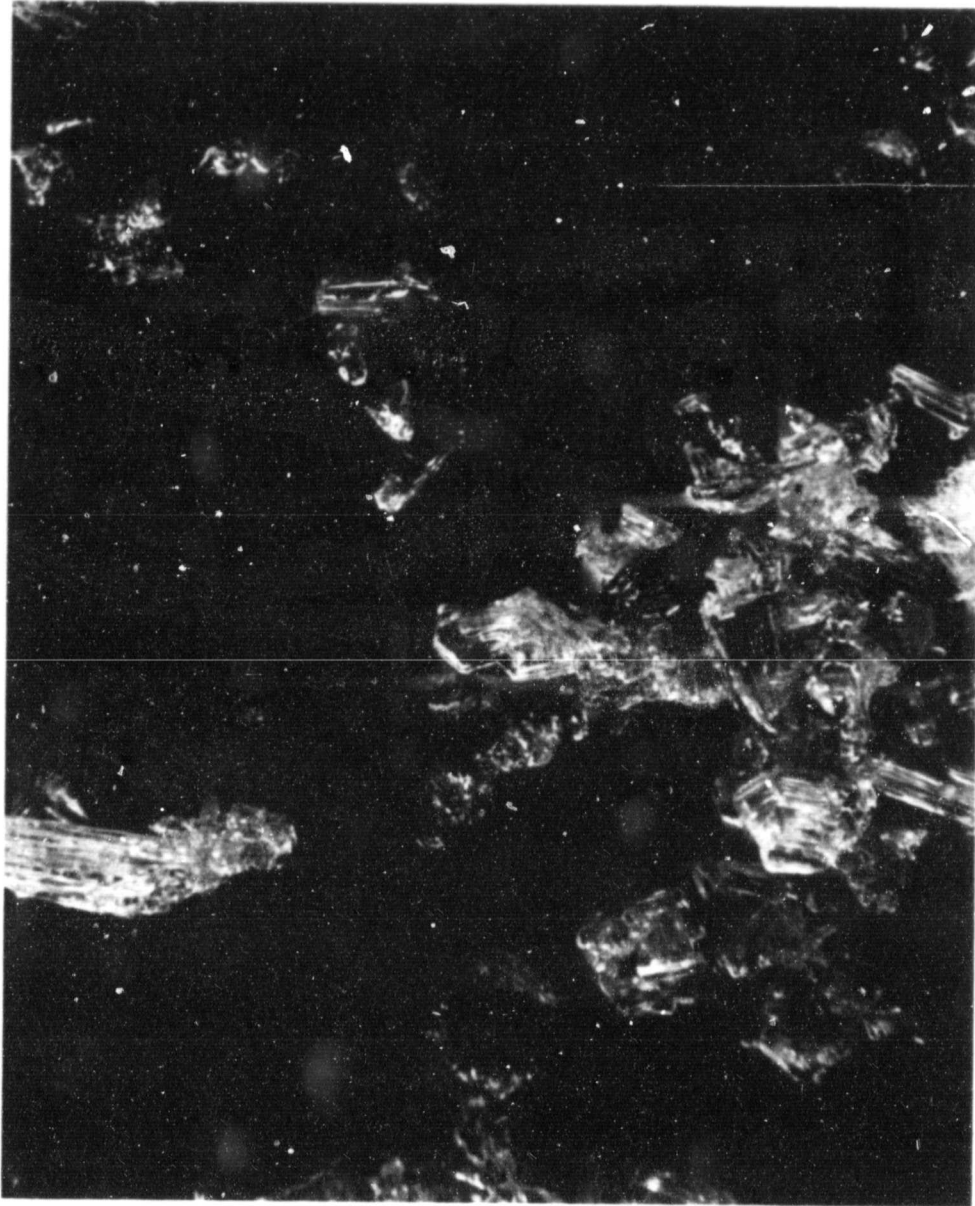
1966. Meteorological classification of natural snow crystals. J. Fac. Sci. Hokkaido Univ. Japan. Ser. VII. II(4): 321-335, 27 plates. (Reprinted by Alta Avalanche Study Center, U.S.D.A. Forest Serv., Wasatch National Forest, Salt Lake City, Utah, Sept. 1968.)

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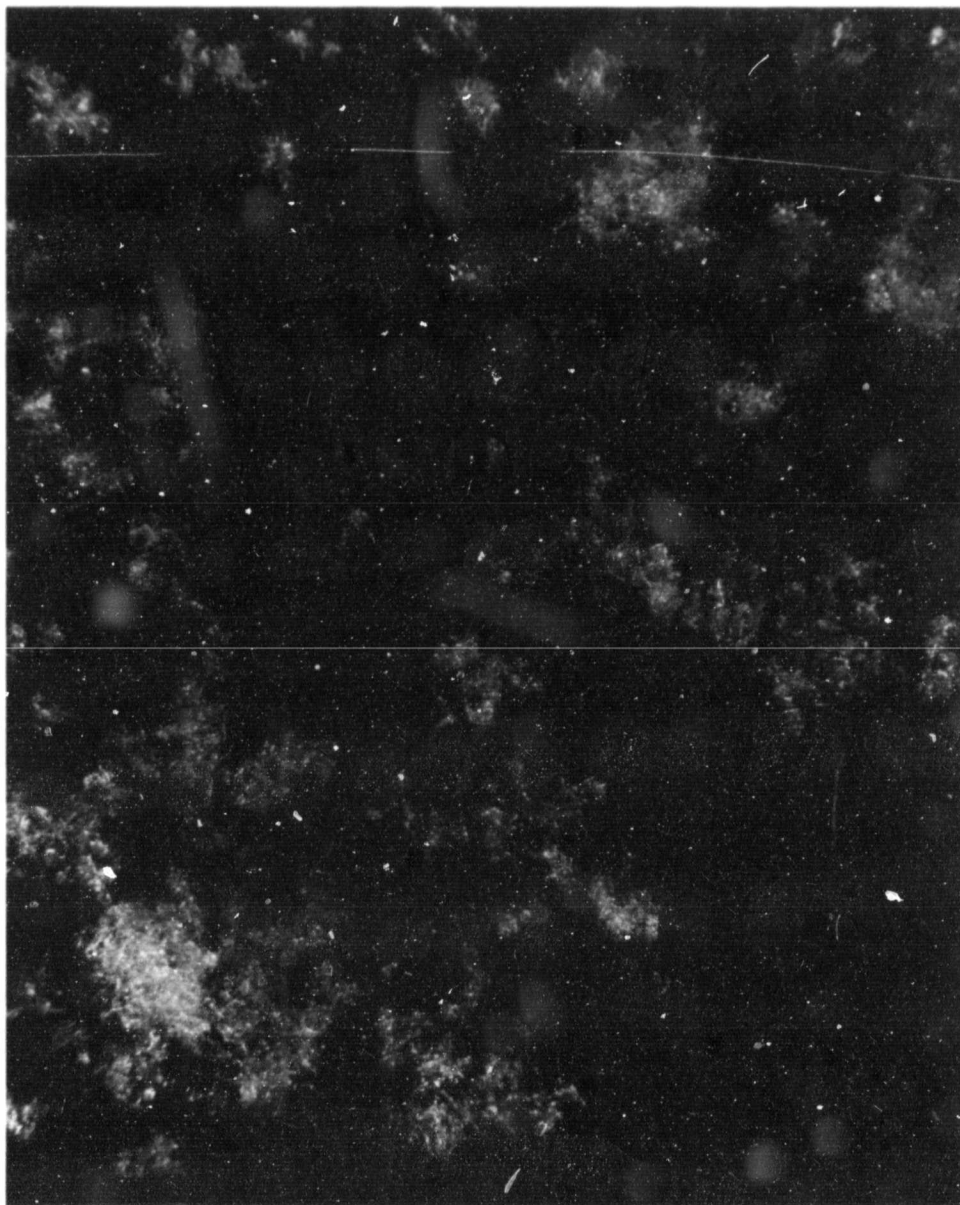


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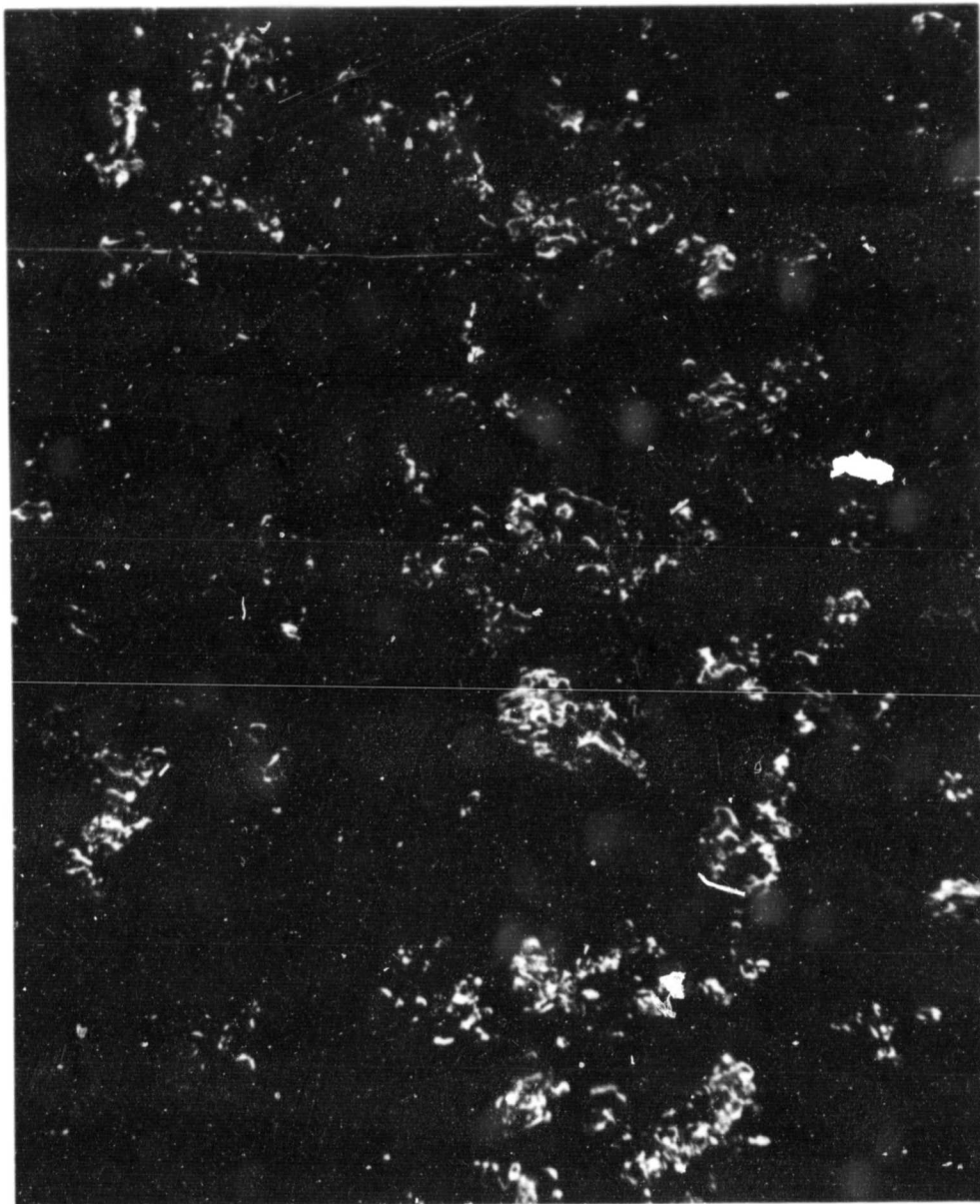
I.C. Surface hoar.

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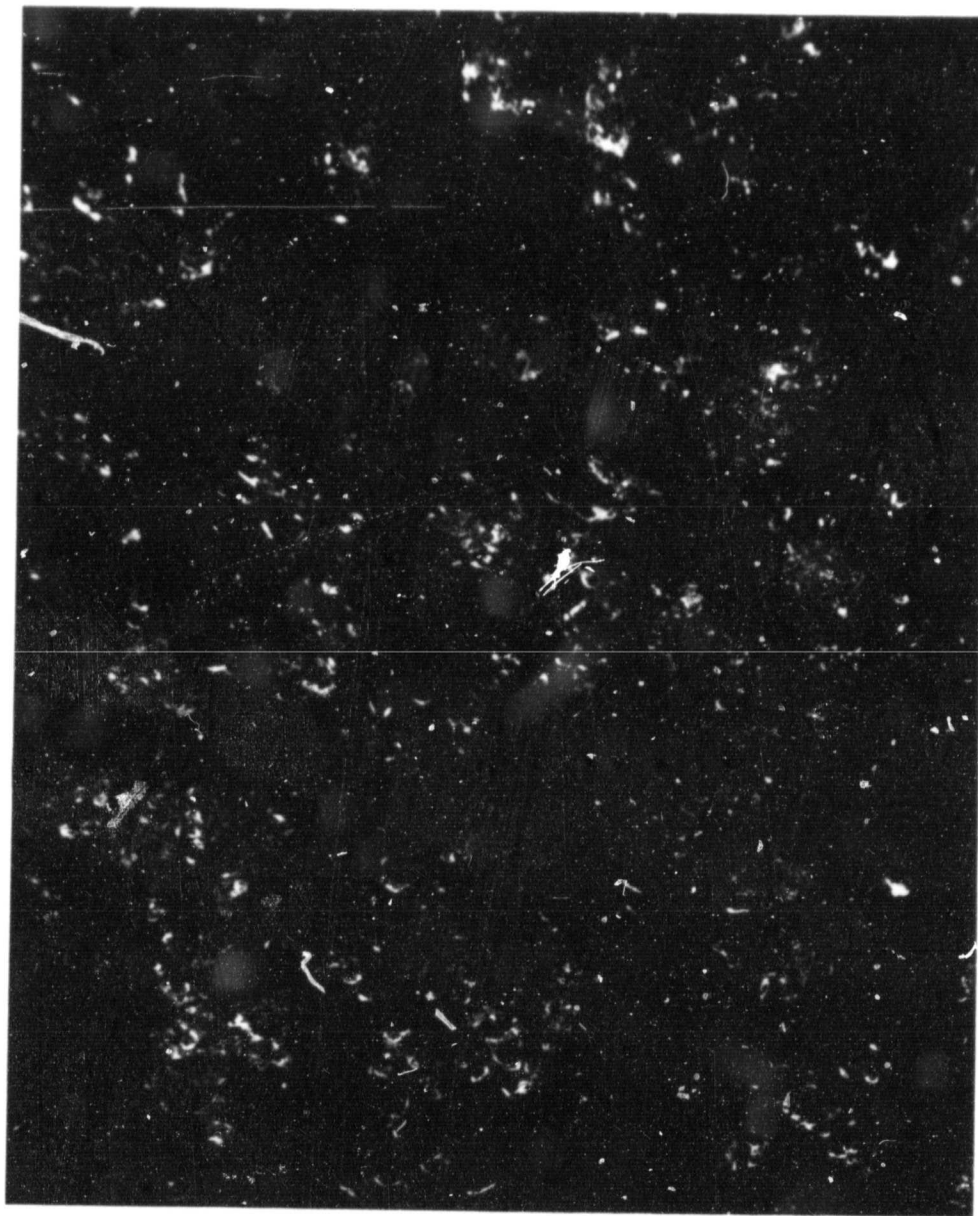
II.A.I. Beginning, decreasing grain size, equi-temperature metamorphism.

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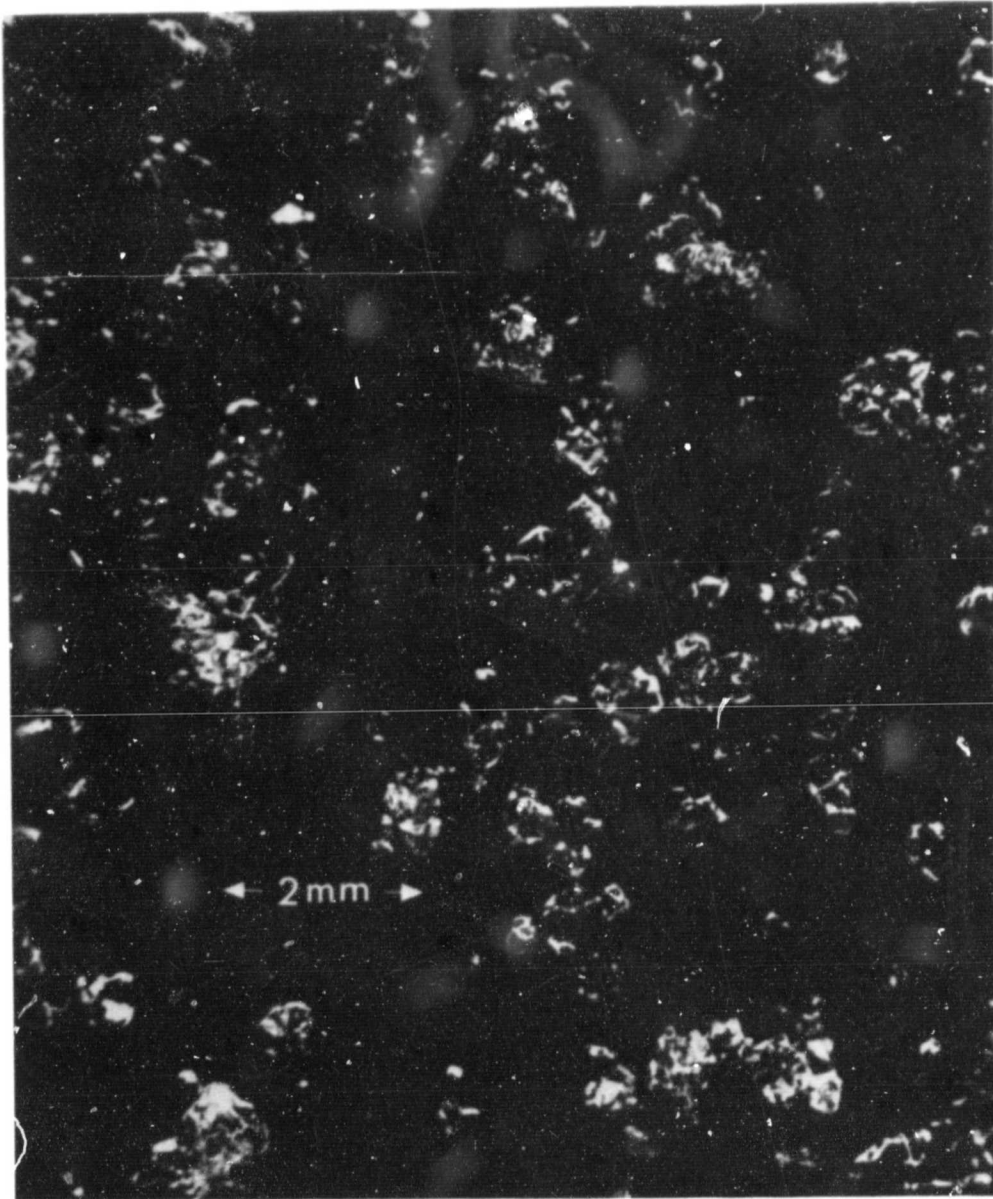
II.A.2. Advanced, decreasing grain size, equi-temperature metamorphism.

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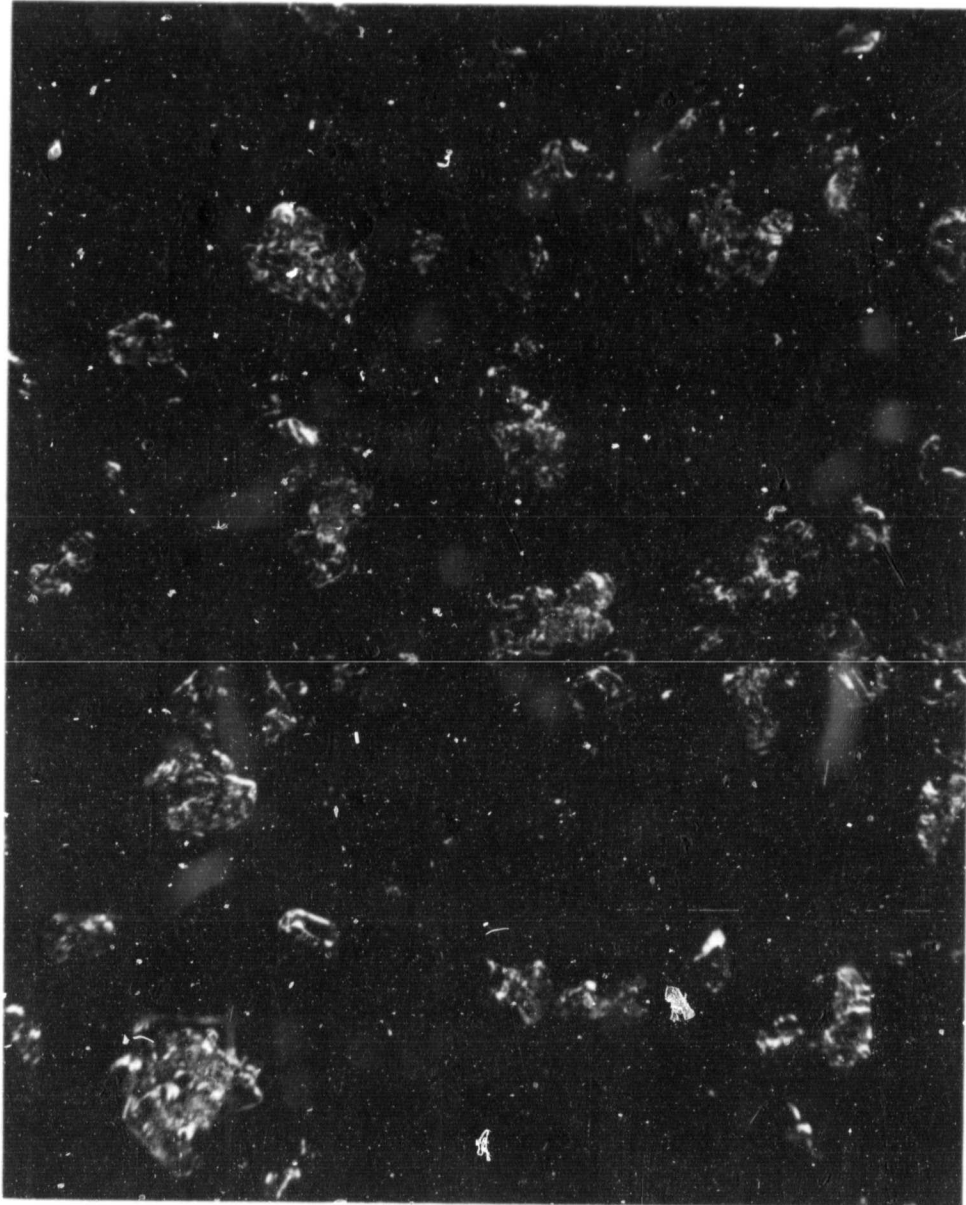
II.B.I. Beginning, increasing grain size, equi-temperature metamorphism.

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II.B.2. Advanced, increasing grain size, equi-temperature metamorphism.

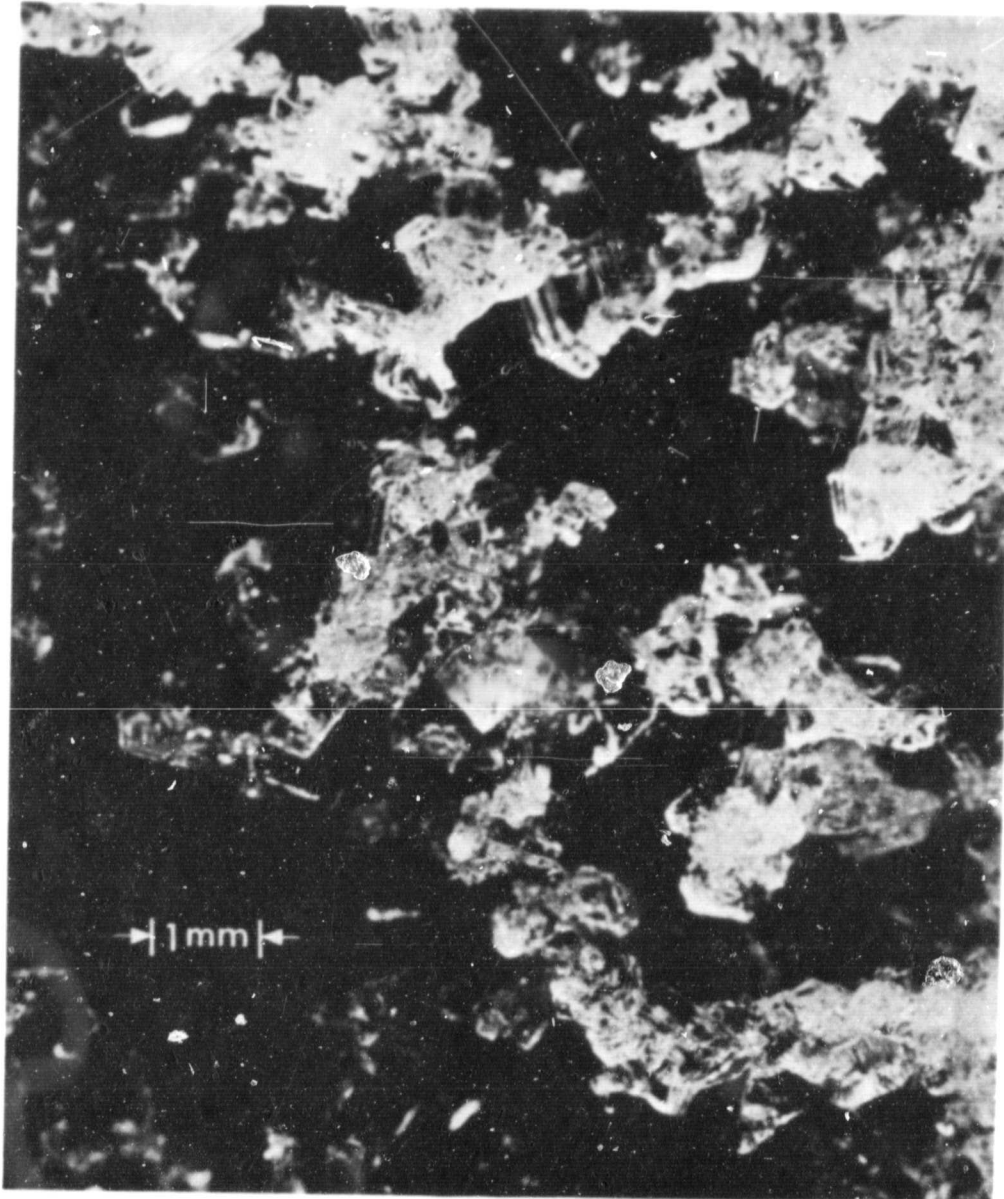
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III.A.I. Beginning, early, temperature-gradient metamorphism.



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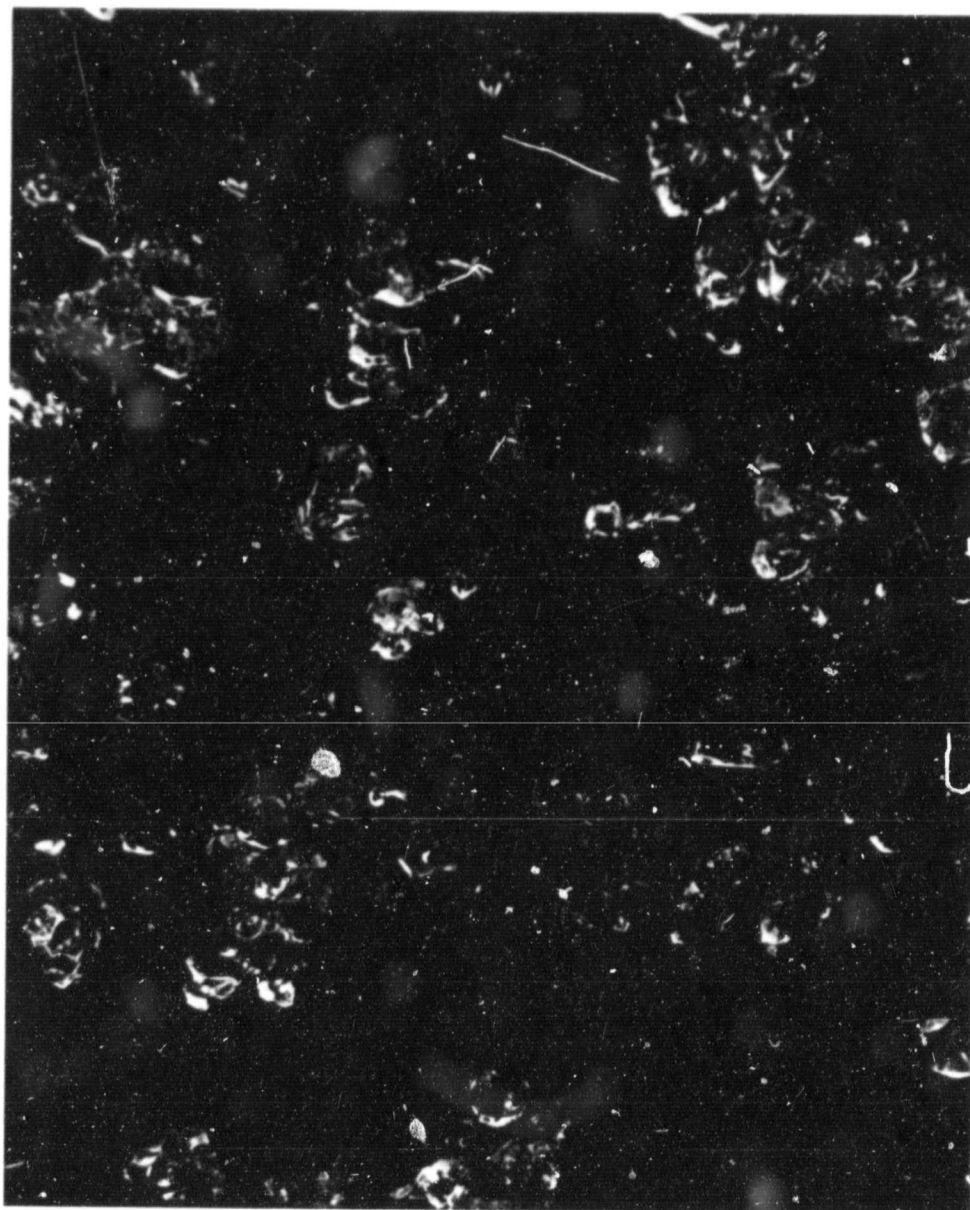
III.A.2. Partial, early, temperature-gradient metamorphism.



III.A.3. Advanced, early, temperature-gradient metamorphism.

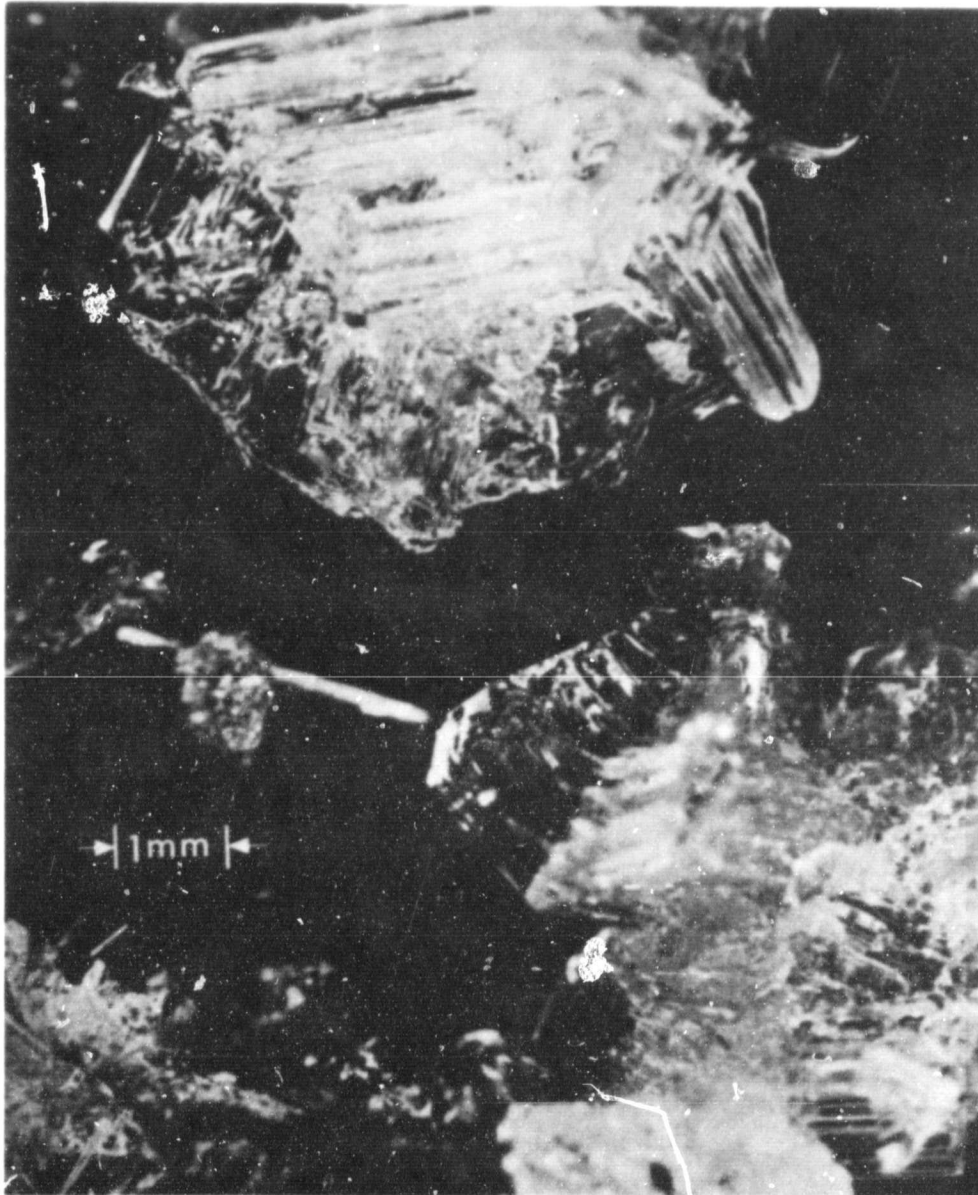


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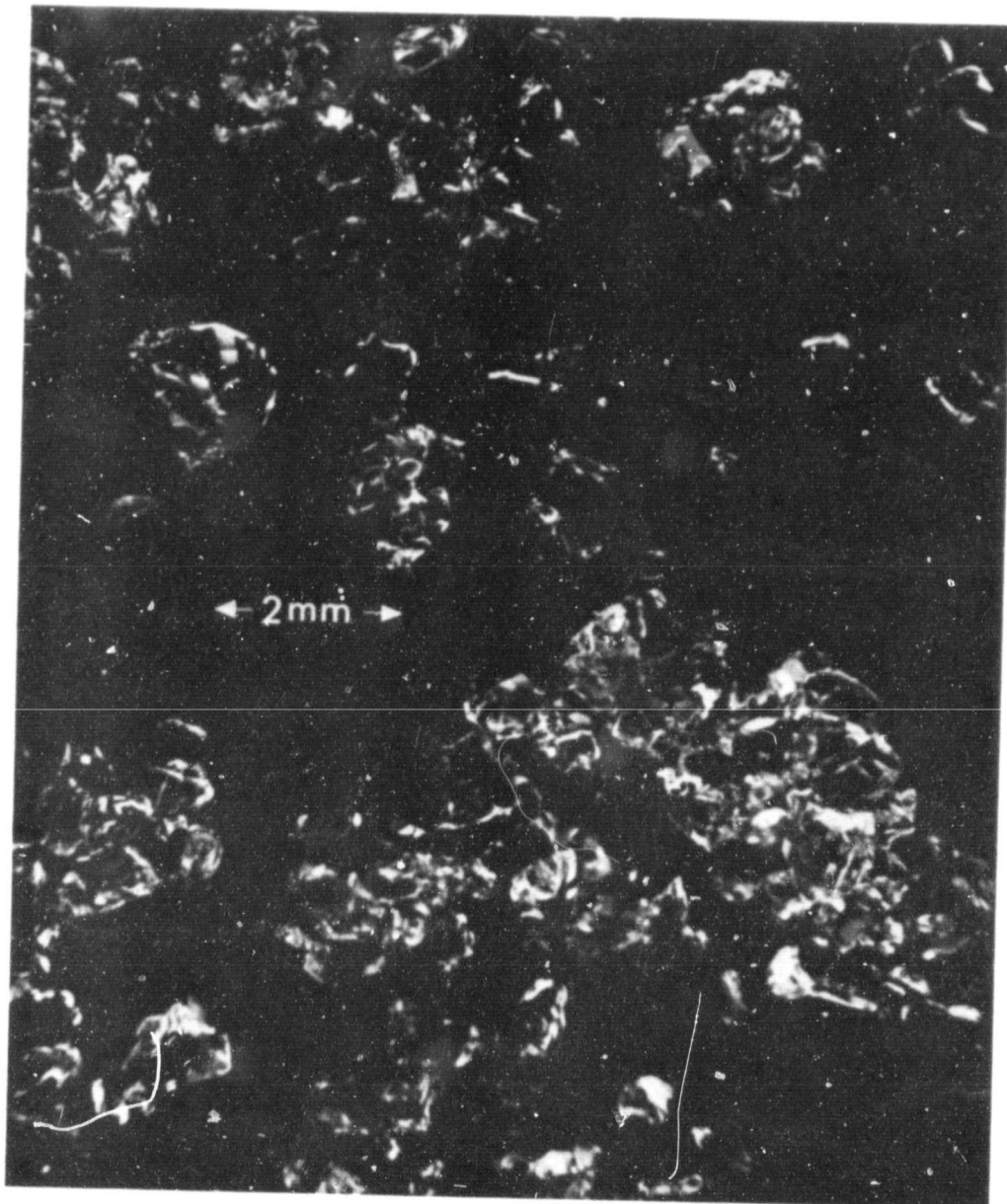
III.B.1. Beginning, late, temperature-gradient metamorphism.

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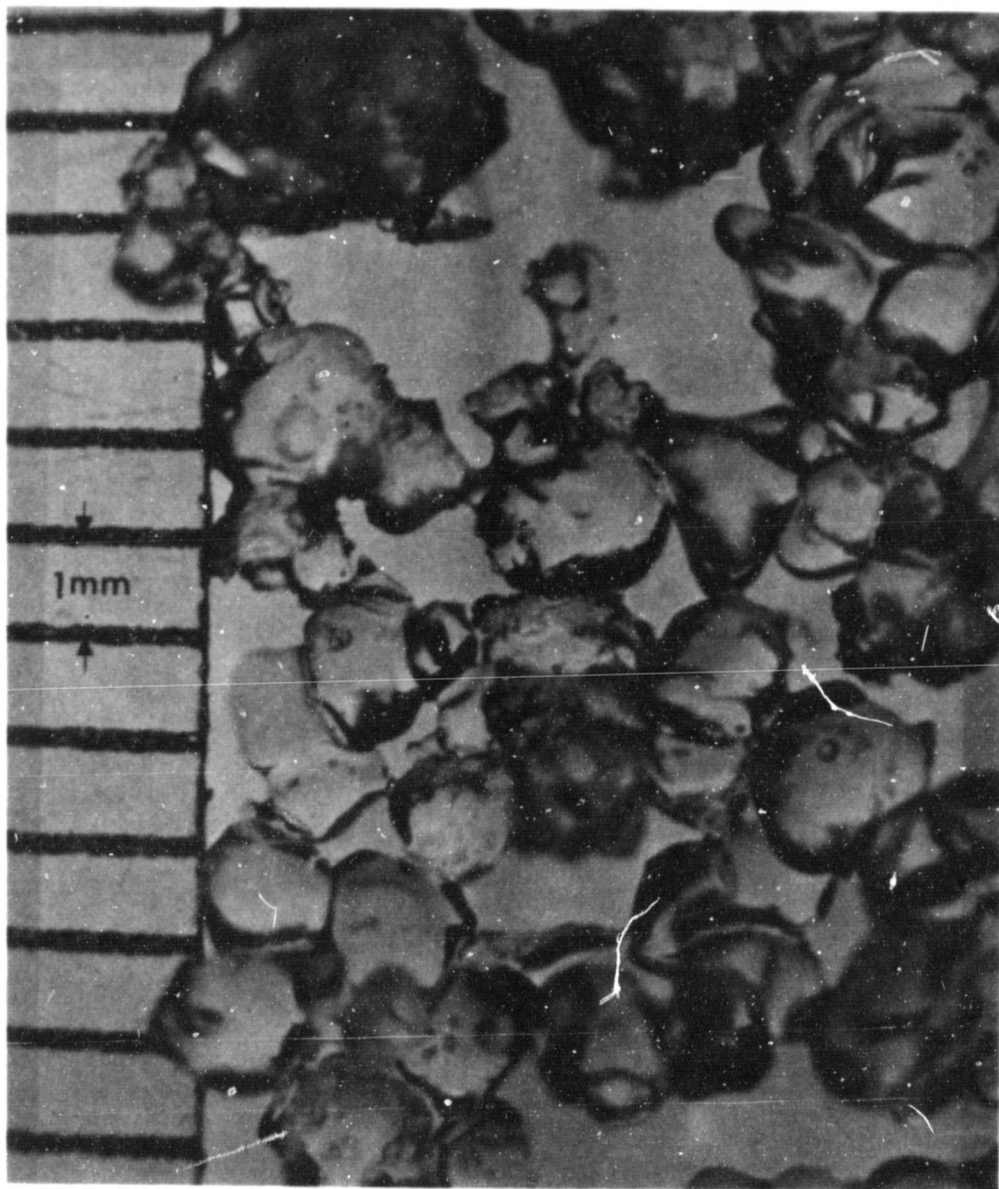
III.B.2. Advanced, late, temperature-gradient metamorphism.

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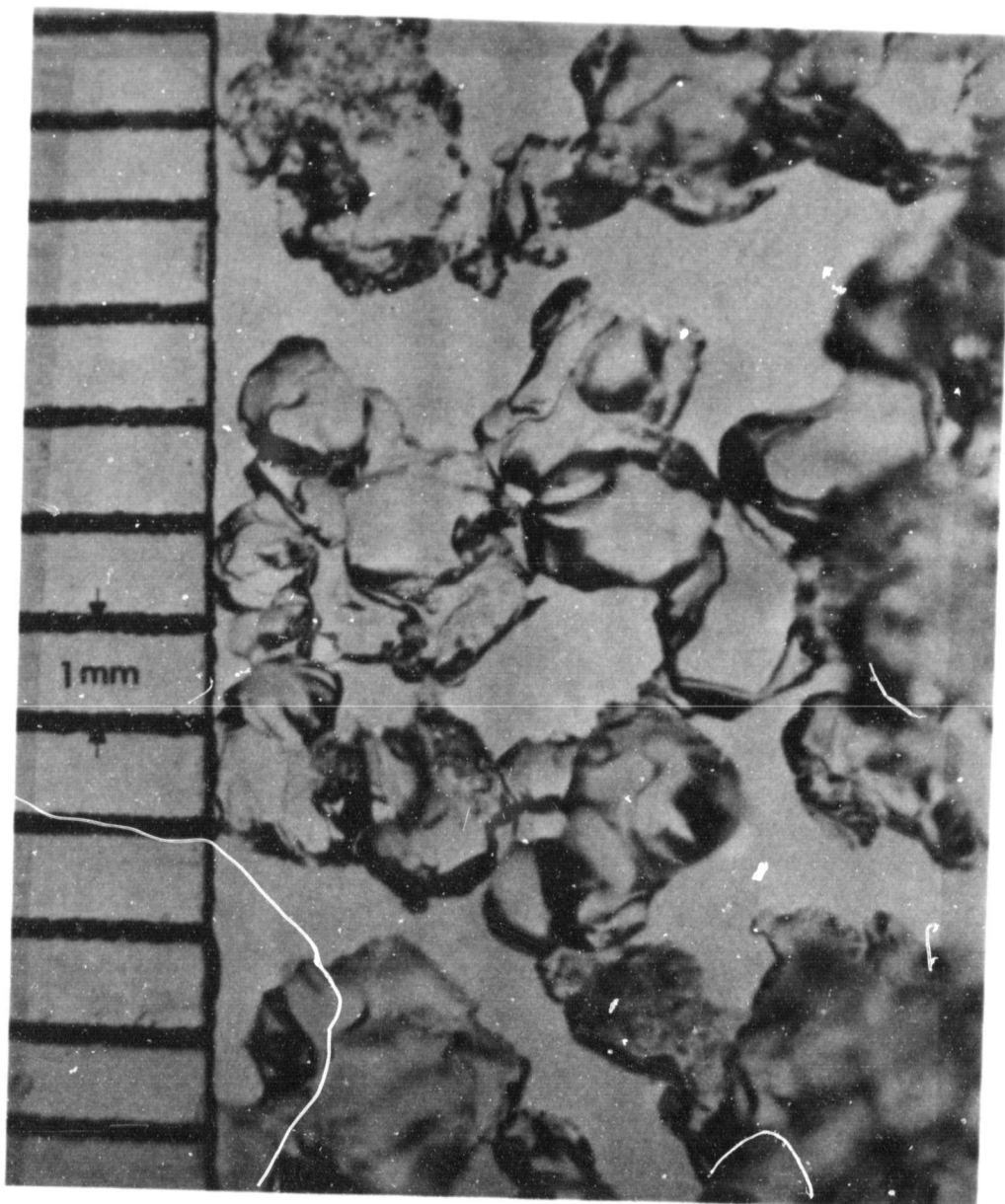
IV.A.1. Limited, melt-freeze metamorphism, firnification.

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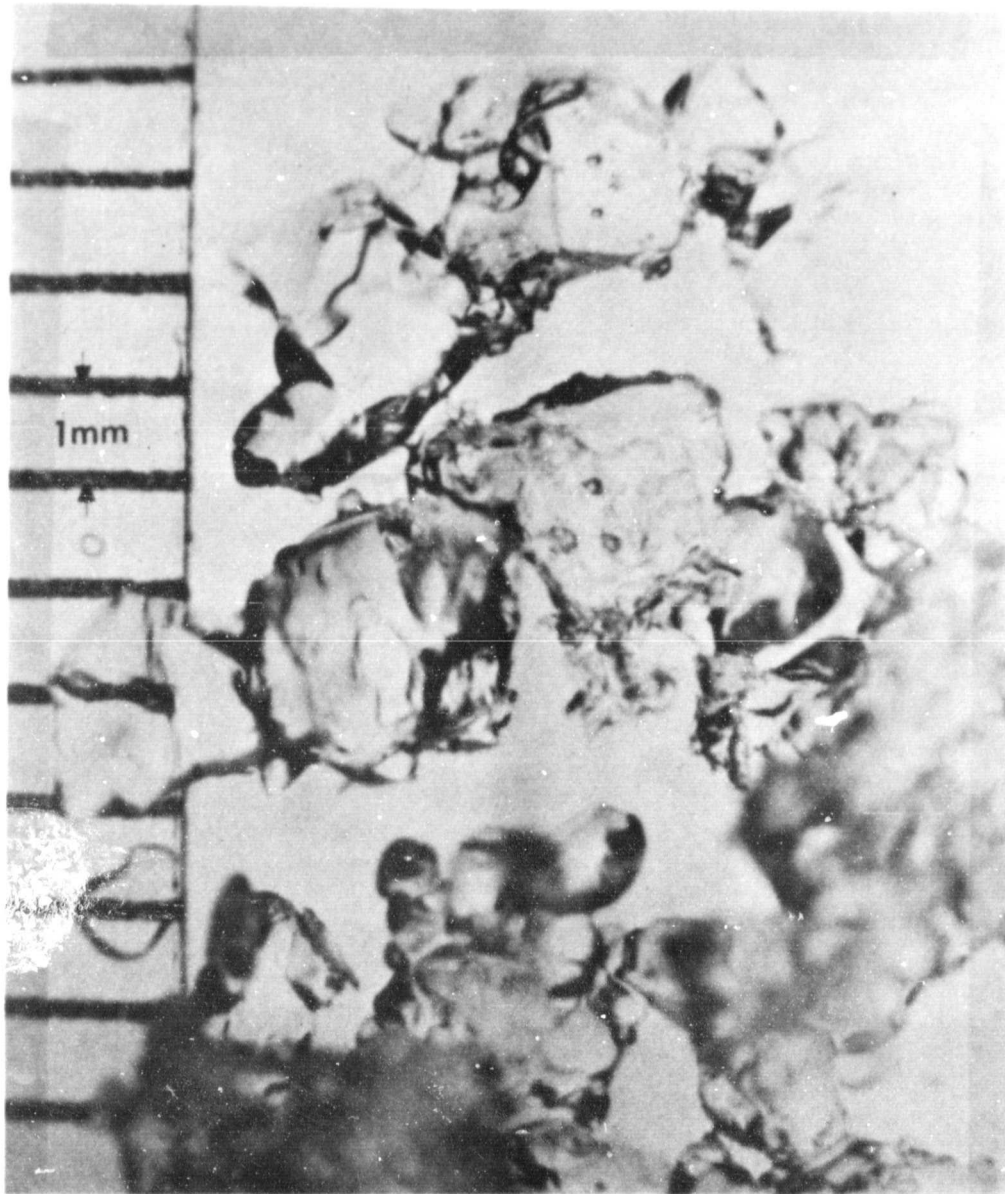
IV.A.2. Advanced, melt-freeze metamorphism, firnification.

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IV.B.1. Beginning, pressure metamorphism, firnification.

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IV.B.2. Advanced, pressure metamorphism, firmification.



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Sommerfeld, R. A.

1969. Classification outline for snow on the ground. U.S.D.A.  
Forest Service Research Paper RM-48, 24 pp., illus.  
Rocky Mountain Forest and Range Experiment Station,  
Fort Collins, Colorado 80521.

A classification of snow on the ground is presented in outline form, with explanations and illustrations of the categories. The classification is based on the physical processes which result in various forms of snow particles. Thus it should be an aid in understanding the physical changes occurring as a snowpack metamorphoses. A list of words commonly used in discussions of snow metamorphism is presented since these words have often been misused.

Key words: snow, metamorphism, firnification

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Key words: snow, metamorphism, firnification

APPENDIX C

Selected portions of a report prepared  
for an actual ground-truth mission in  
April 1980 for areas in Colorado



SNOWPACK CHARACTERIZATION AND  
ASSOCIATED GROUND TRUTH

STEAMBOAT SPRINGS, COLORADO, SITE  
WALDEN, COLORADO, SITE  
RABBIT EARS PASS, COLORADO, SITE

April 7-9, 1980

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June 1980

Mission Report--April 7-9, 1980

Prepared for:

GODDARD SPACE FLIGHT CENTER  
Greenbelt, Maryland 20771  
Contract No. NAS5-26062

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APPENDIX A - Detailed Ground-Truth Data	
Steamboat Springs, Colorado, Site	
April 8, 1980	

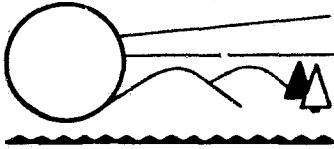
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SNOWPACK CHARACTERIZATION AND  
ASSOCIATED GROUND TRUTH  
April 7-9, 1980



STEAMBOAT SPRINGS, COLORADO, SITE  
RABBIT EARS PASS, COLORADO, SITE  
WALDEN, COLORADO, SITE

INTRODUCTION

This report presents the ground-truth data taken during the period, April 7-9, 1980, at three Colorado sites: Steamboat Springs (Yampa Valley), Rabbit Ears Pass, and Walden. The general locations of these sites are shown in Fig. 1.

The mission anticipated the aircraft flyover about noon of April 8, and the flight occurred as initially scheduled. April 7 was primarily a travel day to the sites, but on the way through Walden, ice depth data were taken at locations on Walden Reservoir. Data were taken at the Steamboat Springs site on April 8 and on the return to Fort Collins on April 9 snowpack data were taken at Rabbit Ears Pass and on the eastern portion of the line at Walden.

The only targets set for this mission were at each end of the first 4 miles of line at the Steamboat Springs site. None were used on Rabbit Ears Pass or at Walden due to surface winds.

Snow-water equivalent values and snow densities were determined using a "Federal" type sampler. No corrections were applied to the water equivalent values.

All data were taken by Resource Consultants, Inc., personnel under the supervision of Dr. E. Bruce Jones. Stephen Olt led the field teams. Assisting in the mission were Jeff Dozier and James Foster of NASA Goddard Space Flight Center.

STEAMBOAT SPRINGS, COLORADO, SITE

The location of the Steamboat Springs site is shown in Fig. 2, and the detailed site location is shown in Fig. 3. This line is approximately 5 miles (8.05 km) in length, oriented in a generally North-South direction in the Yampa Valley a few miles south of the town of Steamboat Springs,





Fig. 2. Steamboat Springs site location.

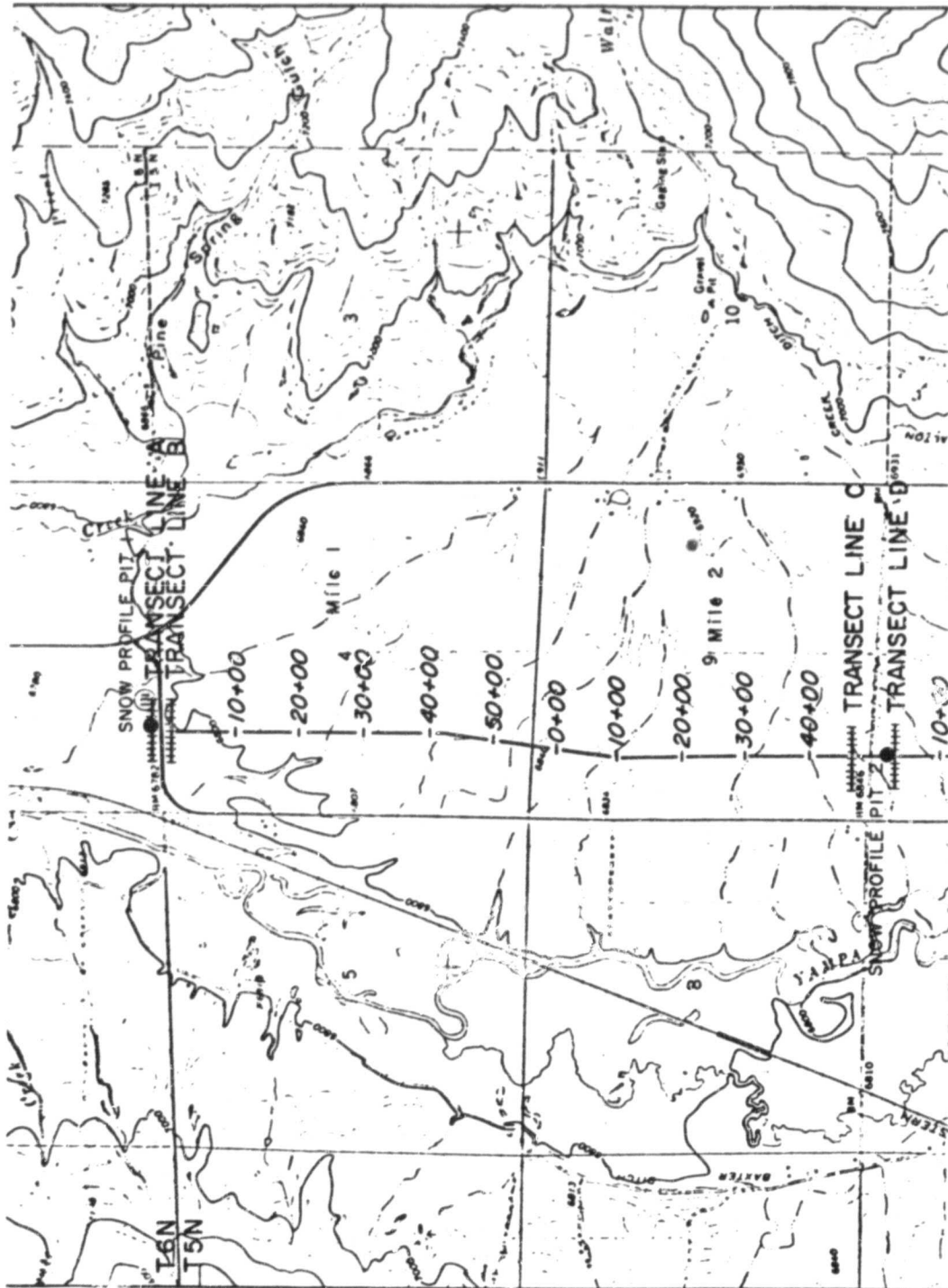


Fig. 3. Typical Section of Detailed Steamboat Springs Site

Colorado. On this mission data were taken over the entire 5 miles. In addition to this primary line, four East-West transects were taken. One snow pit was utilized at this site for establishing the snowpack profile and establishing the point for taking liquid water measurements. The snow pit was at the location shown on Figures 2 and 3 as Pit No. 3.

The northernmost 4 miles of this line traverses generally flat to rolling meadows and pastures. Winter cattle feeding operations have historically been conducted in this valley, hence snowpack disturbances will be noted in those areas in which feeding has taken place. The southernmost mile is fairly hilly terrain with considerable sagebrush.

#### GROUND-TRUTH DATA

##### Steamboat Springs, Colorado, site data

Table 1 sets forth the summary of snow depth, snow density, and water-equivalent measurements taken on the 5-mile line in the Yampa Valley near Steamboat Springs, Colorado. All data at this site were taken on the day of the flight, April 8, 1980, and are presented in detail in Tables A-1 through A-9 in Appendix A.

Table 2 presents the snowpack characteristics obtained at Snow Pit No. 3 (see Fig. 3 for location). Liquid water determinations were also made at this site and these are presented in Table 3. During the activities at this snow pit temperature readings of probes exposed to the sun, shaded, and implanted in the snow about 1 inch were obtained. These are shown in Table 4. No soil-moisture samples were taken of the ground exposed during the digging of the snow pit as some water was noted on the ground surface; under such conditions the results of soil-moisture determinations are somewhat questionable.

C-2

Location 1/	Snow depth				Water equivalent				Snow density			
	Sample points	Mean (in.)	S.D. (in.)	CV 2/	Sample points	Mean (in.)	S.D. (in.)	CV 2/	Sample points	Mean (in.)	S.D. (in.)	CV 2/
Mile 1	57	35.3	3.1	0.09	10	12.7	1.8	0.14	10	34.6	2.6	0.07
Mile 2	54	36.2	3.2	0.09	10	12.0	2.1	0.17	10	33.2	3.2	0.10
Mile 3	51	35.0	2.8	0.08	10	12.5	1.2	0.10	10	35.0	1.7	0.05
Mile 4	49	32.9	3.5	0.11	12	11.8	2.6	0.22	12	37.1	7.2	0.19
Mile 5	53	35.8	6.6	0.18	11	12.4	2.9	0.24	11	35.5	4.5	0.13
Transect B	21	35.1	2.7	0.08	5	12.2	0.7	0.05	5	33.8	1.0	0.03
Transect D	21	32.9	3.2	0.10	5	11.2	1.3	0.12	5	34.9	1.5	0.04
Transect E	11	33.5	0.9	0.03	3	13.5	3.0	0.23	3	40.8	8.1	0.20
Transect G	18	33.1	3.7	0.11	5	12.1	1.8	0.15	5	36.4	4.2	0.12

1/ Locations are shown on Fig. 3.

2/ Coefficient of variation (Standard Deviation [S.D.] divided by the mean).



Table 2  
Snowpack Characterization--Snow Pit #3  
Steamboat Springs, Colorado, Site  
April 8, 1980

Height above the ground at top of layer (in.)	Thickness of layer (in.)	Grain size	Density (kg/m <sup>3</sup> )	Remarks
33.0	0.5	<0.5 mm	375	Very fine rounded crystals
32.5	8.5	0.5-1.5 mm	-	Irregular large rounded crystals with metamorphism
24.0	6.5	0.5 mm average	330	Irregular large crystals with some platelets
17.5	0.5	Ice lens	-	Soft ice lens
17.0	4.0	<0.5 mm	350	Irregular rounded crystals
13.0	0.2	Ice lens	-	Fairly soft lens
12.8	3.8	<0.5 mm	325	Irregular rounded crystals
9.0	1.0	Ice lens	-	Crusty ice lens--relatively firm
8.0	8.0	<0.5 mm	405	Irregular ice crystals, no depth hoar

Table 3

Liquid Water Content of Snowpack  
 (Topmost 1 - 1½ inches)  
Steamboat Springs, Colorado, Site 1/  
April 8, 1980

Run	Starting time (hrs)	Freezing agent	W <sub>1</sub> (gms)	W <sub>2</sub> (gms)	W <sub>3</sub> (gms)	T <sub>1</sub> (°C)	T <sub>2</sub> (°C)	T <sub>3</sub> (°C)	E (gms)	Snow quality
1	1010	Silicon	1358.5	1709.9	1851.2	-39.0	-29.0	0°	92.2	1.003 <sup>2/</sup>
2	1033	"	1357.8	1742.4	1845.4	-42.5	-33.9	0°	92.2	0.986
3	1059	"	1357.3	1712.8	1800.7	-43.0	-35.0	0°	92.2	0.987
4	1140	"	1358.6	1727.4	1843.5	-40.6	-30.3	0°	92.2	0.959
5	1203	"	1358.2	1773.0	1870.2	-44.4	-34.0	0°	92.2	0.908

<sup>1/</sup> All data taken at Snow Pit #3--see Fig. 3 for location.

<sup>2/</sup> This value should be treated as not being greater than 1.000. Values greater than 1.000 are attributed to the slight measurement errors inherent in the system.

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Table 4  
Air Temperature Log at Snow Pit #3  
Steamboat Springs, Colorado, Site  
April 8, 1980

<u>Time</u>	<u>Sun</u> <u>temp.</u> <u>1/</u>	<u>Shade</u> <u>temp.</u> <u>2/</u>	<u>Snow</u> <u>temp.</u> <u>3/</u>	<u>Remarks</u>
0945	0.0	-2.3		Clear skies
0950	1.1	-1.9	-1.0	
0955	0.4	-1.9	0.0	
1000	2.2	-1.2	0.3	Sun hit probe
1005	3.5	-2.2	0.5	
1010	2.6	-2.5	0.6	
1015	7.4	-2.4	0.7	
1020	3.8	+2.3	0.9	
1025	6.4	-1.2	1.5	
1030	5.2	-1.0	2.2	
1035	6.9	-1.9	1.0	
1040	6.5	-1.2	1.0	
1045	5.1	-2.1	1.0	
1050	6.9	-1.6	0.9	No reading
1055	7.3	-0.7	1.0	
1100	5.5	0.3	1.0	
1105	8.4	-1.1	0.9	
1110				
1115	7.8	-1.6	1.0	
1120	4.7	1.2	1.2	
1125	6.2	1.8	1.0	
1130	7.2	0.8	1.0	
1135	5.8	0.3	1.1	
1140	5.6	0.5	1.2	1142 - 2nd pass
1145	4.7	0.8	1.2	1154 - 3rd pass
1150	8.6	0.4	1.2	
1155	9.0	0.5	1.1	
1200	8.3	1.2	0.9	
1205	4.9	1.0	0.8	
1210	4.7	1.7	0.8	

1/ Thermocouple exposed to sunshine.

2/ Thermocouple shaded.

3/ Temperature approximately 1 inch below surface of snowpack.

APPENDIX A

Detailed Ground-Truth Data  
Steamboat Springs, Colorado, Site  
April 8, 1980

Table A-1  
Snow Course Data--Mile 1  
Steamboat Springs, Colorado, Site  
April 8, 1980

Points (North to south)	Depth of snow (in.)	Total wt. (in.)	Tare wt. (in.)	Water equiv. (in.)	Density (%)	Remarks
0+00	--					Start 0954 hrs
1+00	35.0					Zero ski penetration,
2+00	34.0					hard crust on surface,
3+00	32.0					second crust at 29"
4+00	38.0					
5+00	38.0	28.0	14.5	13.5	35.5	Zero ski penetration
6+00	35.0					
7+00	35.0					
8+00	37.0					
9+00	34.5					
10+00	37.0	27.0	14.5	12.5	33.8	1003 hrs
11+00	37.0					
12+00	36.0					Crust at 17 inches
13+00	37.5					Crust at 25 inches
14+00	37.0					
15+00	36.0	26.0	14.5	11.5	31.9	Zero ski penetration
16+00	35.0					
17+00	39.0					
18+00	38.0					
19+00	36.5					
20+00	39.0	30.0	14.5	15.5	39.7	Zero ski penetration
21+00	32.0					Bottom 2 ft. has high
22+00	39.0					density
23+00	42.0					West side of hay storage
24+00	37.0					area
25+00	100	ft. "cattle lane" no readings				
26+00	31.0					

Table A-1 (cont'd)  
Snow Course Data--Mile 1  
Steamboat Springs, Colorado, Site  
April 8, 1980

Points (North to south)	Depth of snow (in.)	Total wt. (in.)	Tare wt. (in.)	Water equiv. (in.)	Density (%)	Remarks
27+00	35.0					
28+00	33.0					
29+00	32.0					
30+00	33.0	26.0	14.5	11.5	34.9	Zero ski penetration
31+00	29.0					
32+00	42.0					
33+00	37.5					
34+00	39.0					
35+00	39.0	28.0	14.5	13.5	34.6	Zero ski penetration
36+00	33.5					1035 hrs
37+00	31.5					
38+00	32.5					
39+00	33.0					
40+00	33.0	26.0	14.5	11.5	34.9	Zero ski penetration
41+00	32.5					
42+00	Middle of ditch, heavy drifting, no sample					
43+00	29.5					
44+00	29.5					
45+00	31.0	24.5	14.5	10.0	32.3	Zero ski penetration
46+00	32.0					
47+00	36.5					
48+00	37.5					
49+00	37.0					
50+00	37.0	26.0	14.5	11.5	31.1	1 cm ski penetration.
51+00	35.5					Snow wet enough to make
52+00	35.0					good snowball.
53+00	38.0					
54+00	32.5					

Table A-1 (cont'd)  
Snow Course Data--Mile 1  
Steamboat Springs, Colorado. Site  
April 8, 1980

Points (North to south)	Depth of snow (in.)	Total wt. (in.)	Tare wt. (in.)	Water equiv. (in.)	Density (%)	Remarks
55+00	41.5	30.0	14.5	15.5	37.4	
56+00	34.0					
57+00	35.0					
58+00	33.0					
59+00	37.0					
n	57			10	10	
$\bar{x}$	35.3			12.7	34.6	
S.D.	3.1			1.8	2.6	
CV	0.09			0.14	0.07	